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RESEARCH REPORT No. 63-54

ULTRASONIC WELDING

OF SELECTED REFRACTORY METALS AND ALLOYS

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FINAL REPORT

June, 1963

Prepared under Navy, Bureau of Naval Weapons

Contract NOw 61-0410-c

AEROPROJECTS INCORPORATED

WEST CHESTER, PENNSYLVANIA

Submitted to

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ABSTRACT

Investigations with thin gages of molybdenum-0.5% titanium alloy, niobium-10% titanium-10% molybdenum alloy, and tungsten showed that these materials are susceptible to ultrasonic welding, and that the strength decay of such ultrasonic welds at 2000°F is not appreciably greater than that of the parent sheet material. Weld cracking tendencies in some instances were attributed primarily to material contamination and in other instances to non-uniform material quality. It was postulated that improved weld quality can be obtained by strict control of material quality and by the use of programmed ultrasonic power and clamping force.

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FOREWORD

This report on the ultrasonic welding of refractory metals and alloys was prepared by Aeroprojects Incorporated, West Chester, Pennsylvania, under Navy Contract No. NOw 61-0410-c. Mr. R. M. Gustafson of the Materials Division, Bureau of Naval Weapons, Department of the Navy, provided liaison and technical assistance. The Contract was administered through the Bureau of Naval Weapons Representative, Morton, Pennsylvania, and Inspector of Naval Material, Reading, Pennsylvania.

The initial phase of the program was performed by R. Frownfelter, with assistance from N. Maropis, Physicist. Later work was done by J. Koziarski. Metallography and the work reported in the Appendix were executed by J. G. Thomas.

Initial efforts were confronted with phenomena such as good metallurgical susceptibility to ultrasonic welding, considerable weld interface ductility, and with tendencies to crack. Extended work, beyond that originally planned, was done in order to provide some explanation of such seemingly contradictory observations.

An extensive study of the literature was made. A number of experienced investigators were contacted personally or by letter. Careful analysis of the data received permitted meaningful partial conclusions concerning one alloy (molybdenum-0.5% titanium) and indications of causes for difficulties in the others.

Difficulties in procuring quantities of refractory metals of known history and uniform high quality was another serious drawback. A number of additional variables were thus induced.

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I. INTRODUCTION AND BACKGROUND

The increasing use of refractory metals and alloys in missile, space vehicle, and atomic applications requires the use of metal joining processes that produce temperature-resistant junctions of structural integrity in both similar and dissimilar metal combinations, with minimal degradation of base material strength and susceptibility to corrosion.

Conventional metal joining techniques, such as fusion welding, depend upon melting the metals to be joined. Where welding is possible using the fusion technique, refractory metals suffer from embrittlement which may be caused mainly by recrystallization, grain growth, and preferential precipitation of impurities. Such bonding processes degrade the physical properties of the original metals and affect their usefulness for applications involving extreme environments.

Ultrasonic welding, a solid-state technique, produces a sound metallurgical bond through the use of high-frequency vibratory energy. No melting of the weld metal takes place, and brittle cast structures are not formed. Although a temperature rise does indeed occur with ultrasonic welding, it does not approach the melting point of the metal.

In ultrasonic welding, the workpieces are clamped together under moderately low static force and exposed to vibratory energy for a brief interval. The mechanism by which bonding takes place has been investigated under Navy Contracts NOas 58-108-c and NOas 59-6070-c, and the results are available in the final reports thereon (1, 2)*.

Depending on the technique and equipment used, a variety of weld types can be produced. These include spot welds, seam welds, ring welds, and area welds. The spot welding technique, where roughly circular weld spots are produced, was used in this program.

A. PREVIOUS EXPERIENCE IN ULTRASONIC WELDING OF REFRACTORY METALS

Ultrasonic welding proved successful as early as 1958 (3) in joining foils of tungsten and molybdenum, 0.005 and 0.010 inch thick, to themselves and each other. Since that time, other refractory and/or high-thermal-conductivity metals and their alloys in various gages have been joined ultrasonically, including niobium (0.005 inch), tantalum (0.005-0.010 inch), titanium (0.025-0.032 inch), 17-7 PH stainless steel (0.005-0.040 inch), high-strength nickel alloys such as Inconel and Inconel X (0.005-0.032 inch),

* Numbers in parentheses refer to references at end of report.

and zirconium, beryllium and others. These welds exhibited an absence of thermally degraded structure in the weld zone, and this work has shown ultrasonic welding to be a feasible and possibly preferable means of bonding these materials.

Certain problems were evident, however. In working with refractory metals, one difficulty involved the sonotrode tips; these sometimes spalled or cracked, wore, or picked up weldment metal. In addition, welding machine settings (power, clamping force, and weld time) appeared more critical than for the more common metals and alloys, to the end that machine settings would have to be somewhat more carefully selected.

B. OBJECTIVES AND SCOPE OF PROGRAM

This program was undertaken to investigate the ultrasonic welding of the following refractory metals and alloys:

a. molybdenum-0.5% titanium alloy
b. niobium-10% titanium-10% molybdenum alloy
c. tungsten.

The initial effort was limited to the welding of thin-gage material covering the range from 0.005 inch to about 0.020 inch. It was planned that the work be subsequently extended to the welding of heavier-gage sheets. However, power requirements for these materials were greater than anticipated, and only the thinner gages could be effectively joined with existing 4-kilowatt ultrasonic welding machines.

Substantial effort was devoted to establishing suitable welding machine settings for the various materials and gages. The results were confounded by variations in the quality of the various lots of material received for the program and the apparent criticality of machine settings for each lot. Weldments were subjected to room-temperature tensile-shear strength tests, and significant results were analyzed statistically to establish the range of strength variability. Extensive metallographic study was carried out for further evaluation of weld quality.

Consideration was given to selection of suitable welding tip materials and configurations, inasmuch as tip sticking and tip pickup had been a problem in prior efforts to weld such materials.

Scouting studies considered the high-temperature strength properties of welds in these materials. This supplementary effort is included herein as Appendix A.

II. EXPERIMENTAL MATERIALS

Experience has indicated that the physical, mechanical, and metallurgical properties of a metal or alloy are related to its ultrasonic weldability. Properties for the molybdenum and niobium alloys, where known, are presented in Table I along with the properties for pure tungsten.

The materials were obtained in gages from 0.005 inch to 0.020 inch, although it was recognized that some of the heavier gages within this range might not be weldable with presently available equipment. Some materials, especially in the early part of the program, could be procured only in random-width and random-length pieces; they obviously were from odd heats. Consequently, they exhibited variation in mechanical and metallurgical properties, and in their response to ultrasonic welding among the various lots. The Department of Defense Refractory Metals Sheet Program is concerned with the standardization of processing techniques and final properties of refractory sheet materials, and this weldability investigation would have been facilitated with the use of materials of uniformly high quality from the Refractory Metals Sheet-Rolling Program. Such material, however, was not available to meet our needs.

When possible, certified test reports were obtained from the fabricator for each lot of material. Such information, however, was not always available for these experimental alloys. Certain properties, such as microhardness and surface roughness, were measured during the program, but it was not possible to conduct comprehensive physical and metallurgical evaluation on all materials used.

Inasmuch as the early stages of the investigation revealed difficulties in welding these materials, but also indicated apparently good metallurgical susceptibility to ultrasonic welding, an extensive review was made of available information, particularly on the two alloys, in an effort to relate the properties to ultrasonic weldability.

A. MOLYBDENUM-0.5% TITANIUM ALLOY

Available information on the various lots of this molybdenum alloy is presented in Table II. Before receipt of the material ordered, preliminary experimentation was carried out with a small quantity of 0.006-inch and 0.011-inch sheet on hand (designated as Lot 1). The processing history of this material was not known, but it appeared to be sheet rolled from ingots prepared by powder metallurgy techniques.

Lots 2, 3, and 4 had been hot-rolled from ingots cast by the consumable-electrode vacuum-arc process. These lots were ordered in the stress-relieved

Table I

SOME PERTINENT PROPERTIES OF REFRACTORY METALS

Property	Unit	Molybdenum-0.5% Titanium (4-6)	Niobium-10% Titanium-10% Molybdenum (7-8)	Tungsten (9-10)
Density	g/cc	10.2	8.06	19.3
Melting Point	^{o}C	2620	2260	3410
	^{o}F	4750	4100	6170
Crystal Structure		bcc	bcc	bcc
Specific Heat	cal/g/^{o}C (20^{o}C)	0.061	0.065*	0.032
Thermal Conductivity	cal/cm^2/cm/^{o}C/sec (20^{o}C)	0.35	0.125*	0.397
Coefficient of Linear Thermal Expansion	cm/cm/^{o}C (20^{o}C)	5.5×10^{-6}	7.1×10^{-6}*	4.98×10^{-6}
Modulus of Elasticity	psi	46×10^{6}	16.5×10^{6}	50×10^{6}
Recrystallization Temperature (1 hour in vacuum)	^{o}C	900 (min.)	1150	1000-1200

* Properties for pure niobium; alloy properties not available.

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Table II

PROPERTIES OF VARIOUS LOTS AND GAGES
OF MOLYBDENUM-0.5% TITANIUM ALLOY
USED ON THE PROGRAM

	Description	Gage, inch	Composition	Ultimate Tensile Strength, psi		Yield Strength, psi		Elongation, percent		Hardness, DPH	Comments
				Longitudinal	Transverse	Longitudinal	Transverse	Longitudinal	Transverse		
LOT 1*	Probably powder metallurgy	0.006 0.011								230** 260**	
LOT 2	Vacuum arc cast, hot rolled, stress relieved, descaled	0.005	0.43-0.50% Ti 0.021-0.025% C	138,200 to 146,100	132,300 to 156,000	110,900 to 131,600	108,400 to 140,200	10-15	4-9	223-282	
		0.010	0.46-0.52% Ti 0.016-0.017% C	132,900 to 141,100	135,700 to 168,000	94,400 to 127,800	103,100 to 132,400	9-13	6-16	262-282	
		0.015	0.48% Ti 0.022% C	137,700 to 139,000	133,000 to 133,600	102,800 to 105,200	101,600 to 102,600	10-12	13	275-289	
		0.020	0.42% Ti 0.034% C	134,400 to 137,900	138,200 to 141,700	117,200 to 118,000	125,500 to 126,800	11-14	8-12	275-297	
LOT 3	Vacuum arc cast, hot rolled, stress relieved, descaled	0.0055	0.46% Ti 0.018% C	138,200 to 143,300	152,300 to 153,600	122,000 to 131,600	139,700 to 140,200	12-13	6-7	262-275	Material was heavily contaminated locally throughout.
		0.008	0.52% Ti 0.04% C	135,100	145,900	125,200	129,900	12	8	275-304	Material received was actually recrystallized.
LOT 4	Vacuum arc cast, hot rolled, stress relieved, descaled	0.010	0.44% Ti	137,200	147,300	129,700	114,400	15	10	283-297	

* Lot 1 material was on hand from a previous program; processing history unknown.

** Measured at Aeroprojects; all other properties were listed in manufacturer's certifications.

and descaled condition, but subsequent metallurgical examination indicated some of the material to be actually recrystallized, and its ductility was substantially lower than that of the stress-relieved material.

As noted in the table, the properties of this molybdenum alloy, provided in the manufacturer's certified tests reports, varied over a significant range. In chemical composition the titanium content varied from 0.42 to 0.52 percent, and carbon content from 0.016 to 0.040 percent. Elongation varied from 9 to 15 percent, and measured hardness from 223 to 304 DPH. Tensile and yield strength values also presented a variation. The ranges of values given for the 0.005-inch and the 0.010-inch Lot 2 material actually represent a compilation of data from three or four different shipments. These variations produced great difficulty and delay in carrying out the intended investigation.

B. NIOBIUM-10% TITANIUM-10% MOLYBDENUM ALLOY

The niobium alloy used in the program was D-31. Available properties of the various lots of materials are presented in Table III. The Lot 1 material was on hand from previous work, and its processing history and properties were not known. Lot 2 was obtained from a pilot production lot for which, likewise, data were not available. The four gages in Lot 3 were ordered in the cold-rolled, stress-relieved condition, but subsequent metallurgical evaluation indicated likelihood of some recrystallization. No information was available on the properties of Lot 4 material. As will be discussed later, Lot 4 showed the same metallurgical characteristics as Lot 3, but exhibited superior weldability.

The chemical compositions given in Table III for Lots 3 and 3a reportedly were those of the billets before rolling and are not necessarily indicative of the compositions of the final rolled sheets. The 0.010-inch material in this Lot 3 was supplied from two different rolling operations; hence the difference in composition.

C. TUNGSTEN

Information concerning the properties of the various gages of tungsten used on the program was not available. This tungsten sheet consisted of four lots of material, as described in Table IV. The material in Lots 1 and 2, although obtained from different suppliers, appeared to be identical; it was all in the as-rolled condition and demonstrated negligible room-temperature ductility; efforts to weld it were but partially successful. In contrast, the Lot 3 material was apparently stress-relieved; its room-temperature ductility was substantially greater than that of Lots 1 and 2 and was estimated, by manual bending, to be about 2 percent.

Table III

PROPERTIES OF THE VARIOUS LOTS AND GAGES
OF NIOBIUM-10% TITANIUM-10% MOLYBDENUM ALLOY

	Description	Composition of Billet	Gage, inch	Ultimate Tensile Strength, psi	Yield Strength, psi	Elongation, percent	Hardness,* DPH	Comments
LOT 1*	History unknown		0.005				258	
LOT 2	Pilot production lot		0.008				246	
			0.010				269	
			0.015				238	
			0.020					
LOT 3	Cold rolled, stress relieved	9.6% Ti,10% Mo,240 ppm O 16 ppm H,62 ppm N,	0.005	81,200	75,800	11	195-207	Material received was actually partly recrystallized.
			0.010	91,500	81,900	18	195-214	
			0.015	98,100	87,900	20	195-214	
			0.020	95,800	88,100	18		
LOT 3a	Cold rolled, stress relieved	10.3% Ti,10.7% Mo, 88 ppm O,25 ppm H, 57 ppm N,1205 ppm C	0.010	97,600	89,600	18	195-210	Material received was actually partly recrystallized.
LOT 4	History unknown		0.005					

* Hardness measurements were made at Aeroprojects; all other properties were listed in manufacturer's certifications.

Table IV

PROPERTIES OF VARIOUS LOTS AND GAGES
OF TUNGSTEN SHEET USED ON THE PROGRAM

	Lot 1				Lot 2	Lot 3	Lot 4	
Description	"As-rolled" from powder metallurgy ingots				"As-rolled" from powder metallurgy ingots	Probably stress relieved	Stress-relief annealed	
Sheet Gage, inch	0.005	0.010	0.015	0.020	0.010	0.010	0.005	0.010
Hardness, DPH**	390	458			376	348		
Surface Roughness, microinches**	10-12	20-24			6-7	10-12		
Ultimate Tensile Strength, psi	120,000 to 300,000 for sheet gages of 0.010 to 0.040 inch.							

* Residual material from another program.

**Properties measured at Aeroprojects.

III. EXPERIMENTAL EQUIPMENT

A. ULTRASONIC WELDING EQUIPMENT

The welding experiments reported herein were carried out with laboratory models of ultrasonic welding equipment having power capacities of up to 4000 electrical watts to the transducers. The transducers in these welders were of laminated nickel, and the coupling systems were of the wedge-reed type, in which longitudinal vibrations from the wedge induce flexural vibrations in the reed to effect shear-type vibration at the welding tip in contact with the sheet being welded. The welding tips and anvils were replaceable.

The welders were equipped with means for precise control over the welding machine settings. A Fluke VAW meter in the circuit between the power source and the transducer provided direct read-out of the high-frequency electrical watts delivered to the transducer. Clamping force was applied by a hydraulic system equipped with a calibrated force gage. Weld time was pre-set by means of an electronic timer.

In addition, special measuring devices described below were utilized in conjunction with the welders for measuring pertinent acoustic characteristics of the transducer-coupling system.

B. WELDING TIPS

The dynamic stresses associated with delivery of vibratory energy to the workpieces during welding impose severe strains on the welding tips, and these may become critical with such materials as the high-strength and refractory metals and alloys. An ancillary phase of this program involved investigations of welding tip materials and configurations for the required metal combinations.

Tips were evaluated in the light of prior experience. Ordinary tool steels had been found to give satisfactory performance and life in welding copper and aluminum and their alloys and low-carbon steel. Inconel X-750 had shown good performance in welding mild steels, titanium, zirconium, and other relatively soft or low-melting metallic materials. However, in attempting to weld the high-strength, high-temperature metals and alloys, particularly those which are hard and brittle, the life of tool steel tips had been short, sometimes less than ten welds per tip; Inconel X-750 proved to be better, but inadequate for production welding of such materials. Investigations under another program (11) of certain other tip materials, including manganese steel, K Monel, René 41, molybdenum, molybdenum-0.5% titanium, and tungsten carbide (some of these materials were used as tapered inserts in steel tips), revealed spalling of the tip with the requirement

for frequent redressing, cracking under the high applied loads, and/or excessive sticking to the weldment. It had been established that welding of the refractory metals and alloys requires tip materials which will not deform, spall, erode, or crack when high vibratory power is applied.

Under a concurrent program (11), extended investigation was made of two new nickel-base alloys which offered considerable promise as tip materials: Astroloy* and Udimet 700**. Pertinent properties of these materials in the fully heat-treated condition are given in Table V. Tips of both materials were found to perform equally well in welding the refractory metals, no spalling occurred with extended usage, and tip cracking and tip sticking to the weldment were substantially less than that obtained with other tip materials.

Most of the welding experimentation reported herein was carried out with tips made of Astroloy. Udimet 700 was also used on a limited scale.

Initially, the welding tips were contoured to a 3-inch spherical radius, which has been generally satisfactory for welding the common metals and alloys in a common range of sheet thicknesses (about 0.020 to 0.060 inch). All experiments were performed with a 3-inch-radius tip except where specifically noted otherwise.

Subsequent to scouting efforts, consideration was given to prior photoelastic investigations (1, 2) which had indicated that a spherical tip radius of 50 to 100 times the thickness of the weldment sheet adjacent to the tip was effective for welding certain metals and alloys in the sheet thickness range of 0.040 to 0.060 inch. This relationship appears also to be effective with the thinner sheets. Consequently, the later experiments involved the use of tips with spherical radii ranging from 0.25 to 1.0 inch.

C. WELDING ANVILS

Most of the welding reported herein was accomplished with a flat-faced anvil as a support for the workpiece. In the early work, this anvil face was made of Inconel X, but Astroloy was also used for this component to minimize pitting of the anvil face and sticking to the weldment.

In connection with the welding of molybdenum-0.5% titanium alloy, a number of weldments was made using an anvil with a concave face. With the wedge-reed transducer-coupling system used for these studies, the welding tip excursions in an arc. When a flat-faced anvil is used, the clamping

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* Originally developed by General Electric Company; presently produced by Wyman-Gordon Company, Worcester, Mass.

** Developed by Special Metals, Inc., New Hartford, N. Y.

Table V

PERTINENT PROPERTIES OF PROMISING WELDING TIP MATERIALS(11)

	Astroloy		Udimet 700		
Composition	56.8 Ni, 15 Co, 15 Cr, 5.25 Mo, 4.4 Al, 3.5 Ti, 0.06 C, 0.02 Fe, 0.3 B		Bal Ni, 17-20 Co, 13-17 Cn, 4.5-5.75 Mo, 3.75-4.75 Al, 3-4 Ti, 1.0 Fe, 0.15 C, 0.1B		
Heat Treatment	2150°F, 4 hr, air cool 1975°F, 4 hr, air cool 1550°F, 4 hr, air cool 1400°F, 16 hr, air cool		2150°F, 4 hr, air cool 1975°F, 4 hr, air cool 1550°F, 24 hr, air cool 1400°F, 16 hr, air cool		
Mechanical Properties at Temperature, °F	Room	1400	Room	1400	1800
Tensile Strength, psi	190,000	150,000	204,000	150,000	52,000
Yield Strength, psi	138,000	122,000	140,000	120,000	44,000
Elongation in 2 in., %	12	15	17	33	28
Reduction of Area, %	13	16	20	40	28
Stress Rupture					
Temperature, °F	1400		1400	1800	
Time, hr	23		48	48	
Strength, psi	85,000		85,000	20,000	

force at the extremes of the arc may be slightly reduced over that obtained at the center. Such alleviation of clamping force at the excursion extremes degrades the conditions for good welding. The anvil face was therefore provided with a concavity approximating the arc radius described by the tip.

D. INSTRUMENTATION OF ULTRASONIC WELDER

In addition to the standard ultrasonic welder instrumentation for precise control of frequency, power, clamping force, and weld time, the laboratory welders used were equipped with devices for measuring vibratory energy delivery to the weldment and tip displacement.

1. Standing-Wave-Ratio Equipment

Prior theoretical and experimental studies (1, 2) had established the efficacy of determining the power transmitted through an ultrasonic coupler (and hence the efficiency of electrical to mechanical energy conversion) by measurement of the standing-wave-ratio in the coupler. For making such measurements during welding, the coupler is equipped with standing-wave-ratio sensing elements spaced at one-quarter wave intervals along the rod. The electrical outputs of these elements were fed through an amplifier to the deflection plates of an oscilloscope, and the area of ellipse pictured on the oscilloscope is then proportional to the acoustic power transmitted through the coupler.

2. Tip Displacement Measuring Device

Under certain specific conditions, the vibratory energy delivery to the welding tip can be related to the tip displacement during welding. In order to evaluate this parameter and to determine variation in tip displacement during a single weld cycle, the experimental welder was equipped with suitable measuring and recording systems. In some instances, a phonograph pickup was mounted on one side of the welding tip, and the deflection was thus measured. For a few experiments, a single sensing element was installed on a wedge-reed type coupler at a point where its output corresponded to the minimum particle displacement in the coupler. The output from this sensing element was fed through an amplifier to a Brush strip-chart recorder to provide an indication of tip displacement as a function of time during the welding cycle.

3. Weld Zone Temperature Measuring Equipment

Although not attached to the ultrasonic welder, an equipment array was assembled for determining interfacial temperatures in the weld zone during weld formation, based on a single-wire thermal emf technique previously developed and refined (1).

A thermocouple junction was prepared consisting of the weldment itself and a single wire (No. 40 gage Constantan) potted into the zone of

the intended weld. The temperatures indicated by this thermocouple were recorded with a Brush d-c amplifier and strip-chart recorder so that temperature variation during the time of a single weld cycle could be determined and evaluated.

IV. EXPERIMENTAL PROCEDURES

A. GENERAL WELDING PROCEDURES

1. Welding Machine Performance

Satisfactory performance of the ultrasonic welding equipment is established prior to any particular investigation as follows: At least five specimens of 0.040-inch bare 2024-T3 aluminum alloy (or, in some instances, of 0.025-inch Type 302 stainless steel) are welded with fixed (optimum) machine settings and tested in tensile-shear. When all weldments exhibit strengths within a given narrow range (above about 900 pounds for the aluminum alloy), the welder is operating satisfactorily. Otherwise, the source of difficulty is located and adjustments made before initiating welding of the refractory materials. This procedure was followed throughout this program.

2. Specimen Surface Preparation

Experience has shown (12) that surface preparation of the parts to be joined is generally not critical to the ultrasonic welding process. Usually all that is required is the removal of loose surface contamination by degreasing.

Unless otherwise noted, all specimens were prepared by degreasing either in A-27 Pennsalt detergent solution or in acetone. In addition, some of the specimens were lightly abraded with No. 400 emery paper before welding to remove adherent surface films and surface roughness. One study in the welding of molybdenum-0.5% titanium involved pre-etching of the surfaces; the specimens were electropolished at 10 volts for 10 seconds in an aqueous solution of 10 volume percent sulfuric acid and 5 volume percent chromic acid, then were rinsed in warm water and air dried.

3. Welding Tip Dressing

With these refractory metals and alloys, it was found that occasionally the weldment would stick to the welding tip and/or anvil, and when pulled loose would leave weldment metal adhering to tip or anvil surface. In some instances tip pickup was excessive and frequent redressing was required, sometimes after every three or four welds. Usually this phenomenon could be attributed to unfavorable welding machine settings.

B. WELDING MACHINE SETTINGS

The production of a sound weld depends upon appropriate selection of each of three operating variables: Power, clamping force, and weld time.

The power is usually specified in terms of high-frequency electrical power delivered to the transducer, since this is more readily measured and indicated during welding than actual acoustic power delivered from the transducer through the coupling system to the weldment. Static clamping force, which is usually applied hydraulically through the welding tip, assures the necessary intimate contact and impedance matching (2) (and hence maximum vibratory energy transmission) between the welding tip and the weldment. Weld time, adjustable by means of the electronic timer, dictates the amount of energy transmitted at a given power level.

These welding machine settings vary as a function of the properties of the material to be joined and as a function of sheet thickness. In the ultrasonic welding of the common metals and alloys, these settings are usually not critical, although there is a well-defined range of each setting within which the most satisfactory welds are produced for a given material and material thickness combination. These settings, however, are more critical for refractory metals.

1. Calculated Energy and Power Requirements

The weldability of a given material has been defined as the amount of energy (i.e., the product of power and weld time) required to produce a sound weld. Previous experience (2) based on examination of a wide range of materials of varying material properties has resulted in an empirical equation for predicting the approximate minimum electrical energy into magnetostrictive transducers required to produce good monometallic welds with reasonable time intervals in the range below about 1.5 second:

$$E = 316 \ H^{1.5} \ t^{1.5},$$

where E = electrical energy supplied to the transducer of a spot welding machine, in watt-seconds,

H = Diamond Pyramid Hardness number (DPH) or Vickers Microindentation Hardness number (VHN), and

t = thickness of the sheet adjacent to the welding tip, in inches.

This equation was used to estimate the electrical energy required to weld each of the refractory materials in the gages of interest (0.005 to 0.025 inch). The results are presented in column 4 of Table VI.

Previous experience has furthermore indicated that in order to obtain a good weld in a hard material, particularly a material with low ductility in the intermediate temperature range, the weld time should be short (a fraction of a second). Therefore, the calculated energy requirements have been used to compute power requirements for weld times of 0.3, 0.5, 0.8, and 1.0 second. These calculations are also presented in Table VI, and the data are plotted in Figure 1.

Table VI

CALCULATED ELECTRICAL ENERGY AND POWER REQUIREMENTS
FOR ULTRASONICALLY WELDING THREE REFRACTORY MATERIALS

Metal	Gage, inch	Hardness, DPH	Required to Weld: Electrical Energy, watt-sec	Power (for indicated time), watts: 0.3 sec	0.5 sec	0.8 sec	1.0 sec
Mo-0.5 Ti	0.005	269*	500	1,670	1,000	625	500
	.010	269*	1,450	4,830	2,900	1,810	1,450
	.020	285	4,260	14,200	8,520	5,330	4,260
	0.025	285	6,000	20,000	12,000	7,500	6,000
Nb-10 Mo-10 Ti (D-31)	0.005	258*	460	1,530	920	580	460
	.008	246*	870	2,900	1,740	1,090	870
	.010	269*	1,100	3,670	2,200	1,375	1,100
	.015	238*	2,200	7,330	4,400	2,750	2,200
	.020	240	3,200	10,670	6,400	4,000	3,200
	0.025	240	4,600	15,330	9,200	5,750	4,600
Tungsten	0.005	390*	850	2,830	1,700	1,065	850
	.010	458*	3,000	10,000	6,000	3,750	3,000
	.020	450	8,500	28,330	17,000	10,625	8,500
	0.025	450	11,500	38,330	23,000	14,375	11,500

*Hardness values measured at this laboratory; other values estimated.

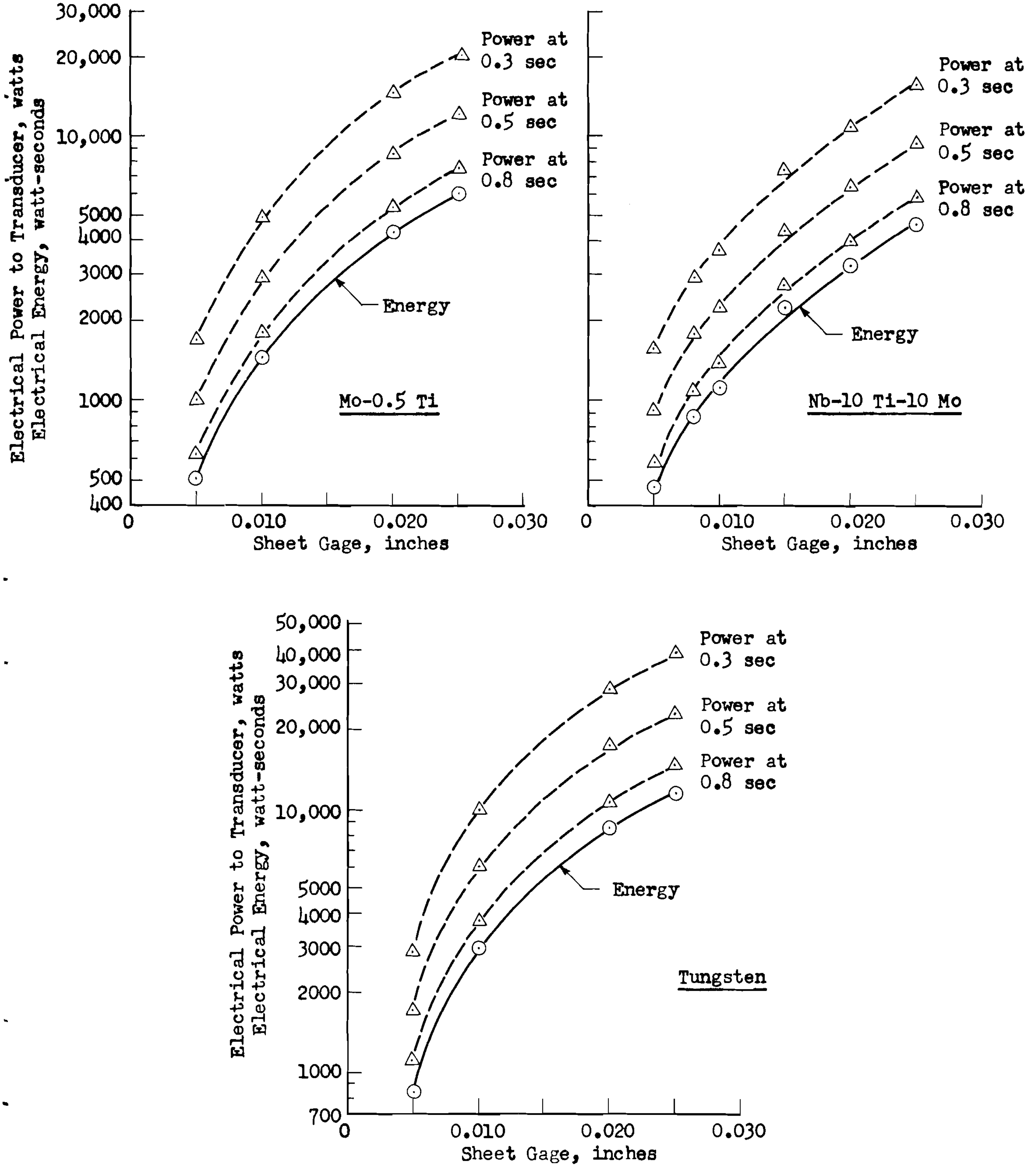

Figure 1

CALCULATED ELECTRICAL ENERGY AND POWER REQUIREMENTS
FOR WELDING EACH OF THREE REFRACTORY METALS AND ALLOYS

It will be noted that with a weld time of 0.8 second, the maximum thickness of D-31 alloy that can be welded with 4000 watts of electrical power is 0.020 inch; the maximum with molybdenum-0.5% titanium is slightly less than 0.020 inch; and with tungsten the maximum is 0.010 inch. These calculated data support previous predictions concerning the relative difficulty of welding tungsten.

The data presented in Table VI and Figure 1 were used as a point of departure for establishing effective welding conditions for joining these three materials.

2. Determination of Required Clamping Force

Experimentation has shown that for a given power level there exists an optimum clamping force for welding a given material. A clamping force below this optimum will not insure the best impedance match into the weldment nor adequate contact between the weldment components. On the other hand, if the clamping force is too high, the welding tip will be restrained from lateral excursion and no weld will result.

A definitive relationship between clamping force and power for a given thickness of a specific material can be evolved by means of a threshold curve which defines a minimum energy condition (MEC) for producing effective welds, i.e., establishes the clamping force at which the required power is minimum. There are several techniques for establishing such a threshold curve.

a. Weld Peel Technique

For relatively thin gages of reasonably malleable materials, the clamping-force-vs.-power welding threshold curve has been determined by producing welds over a range of clamping forces and power levels and testing each weld specimen by manual peeling. The fractured surfaces of the peeled welds are examined and the welds are evaluated qualitatively as follows:

(1) Good weld: nugget pulled from one sheet, encompassing weld envelope.

(2) Moderate weld: partial nugget, pulled from only a portion of the weld envelope, or significant weld demonstrated without a weld nugget.

(3) Partial bonding: some metal transfer, but no weld of substantial strength.

(4) No bonding.

A single clamping force setting and a fixed weld time are arbitrarily selected and welding is accomplished at progressively decreasing power until the bond no longer fails by nugget tear-out. The welding threshold is assured to exist at the power level where the weld can be rather easily peeled. The powers used herein may be approximated from the calculated energy requirements such as those presented in Table VI. This procedure is repeated at other clamping force settings (with the same weld time) until sufficient data are accumulated to produce a plot of power vs. clamping force at the threshold level, which is a concave upward curve for welding. It appears that the minimum point on this curve, i.e., the clamping force at which minimum power is required, corresponds to the condition of best impedance match into the weld zone and thus, best welding.

For brittle materials such as tungsten, the manual nugget pull-out peel test is clearly not feasible and it appeared that this would also be true of the thicker gages of molybdenum-0.5% titanium and D-31 alloy. These materials do not deform as readily as the more ductile materials, high stress concentrations are produced at the edge of the weld because of their stiffness, and peel may result in a type of failure which could be mistakably identified as a nugget, a partial nugget, or no nugget.

b. Tensile-Shear Technique

The same type of threshold information as that obtained with the peel test may also be developed by testing welds in tensile-shear, and plotting the power vs. clamping force curves on the basis of weld strength. Such a test is more objective, and the effect of high elastic modulus and low ductility are thus eliminated.

c. Weld Interface Temperature Technique

When vibratory energy is delivered through the welding tip to the metals being joined, a portion of this energy produces elastic and plastic deformation in the weld zone, generating heat and resulting in an associated temperature rise at the weld interface. This temperature rise is extremely transient and localized, does not produce melting of the welding components, and is generally within the range of 35 to 50 percent of the absolute melting point (2). Studies in our laboratories and elsewhere (13-15) have been made of this temperature rise as a function of weld time, clamping force, and power (or vibratory amplitude), of the relationship between temperature and bond strength, and of the rate of temperature rise.

In particular, it has been demonstrated that the interface temperature rise obtained at any fixed and reasonable power level is maximum at the clamping force productive of a best impedance match (see above). There thus appears to be a correlation between temperature rise and the clamping force for the most efficient energy delivery into the weld zone. Measurement of this temperature rise in the weld zone at fixed power settings and at several values of clamping force can therefore be used to plot a concave downward curve for temperature rise vs. clamping force, and the optimum clamping force is the highest point on this curve.

In this investigation, interfacial temperatures were determined by the single-wire thermocouple technique described in Section III. Such measurements made at fixed power levels and over a range of clamping forces provided data for the temperature-clamping force curves, and the maximum temperature indicated the optimum clamping force.

This technique has limitations when applied to very thin materials because of the difficulty in locating the wire precisely so as to sense the maximum interfacial temperature.

d. Standing-Wave-Ratio Technique

The standing-wave-ratio (SWR) instrumentation described in Section III also provides a means for determining optimum clamping force, inasmuch as the area of the SWR ellipse on the oscilloscope is proportional to vibratory energy transmission, i.e., maximum ellipse area is obtained with the best impedance match (maximum vibratory energy transmission into the weldment).

At a given power level, SWR ellipse areas were determined at various clamping force values for selected gages of the materials of interest. In each case, the ellipse portrayed on the oscilloscope was photographed during weld formation and the area subsequently measured with a planimeter. Plots of the SWR ellipse area vs. clamping force provided a concave downward curve; the highest point on this curve represented the best energy delivery into the weldment and hence the optimum clamping force. This technique has been used with both thick and thin materials.

3. Determination of Weld Time

Prior experience in ultrasonic welding of refractory metals and alloys has indicated that too long a weld power pulse is detrimental to weld quality and to the materials being welded. Welds may form but can be broken with continued application of vibratory energy, and the excess energy can produce fatigue cracks. With a given energy required for welding, bonds are generally of higher quality when produced with high power levels and short weld times, rather than with lower powers and longer times.

Efforts during this program to optimize weld time yielded inconclusive results. Determinations of the relative power delivery to the weldment were therefore made in terms of tip deflection as a function of time of vibratory energy application.

It appeared that tip displacement for effective bonding follows the pattern shown in Figure 2. At the initiation of the vibratory energy pulse (Region a in Figure 2), the tip displacement is maximum. This is attributed to a brief incipient coupling period, during which essentially all the power delivered may be dissipated as heat due to sliding friction between the tip and the sheets to be welded or between the sheets themselves.

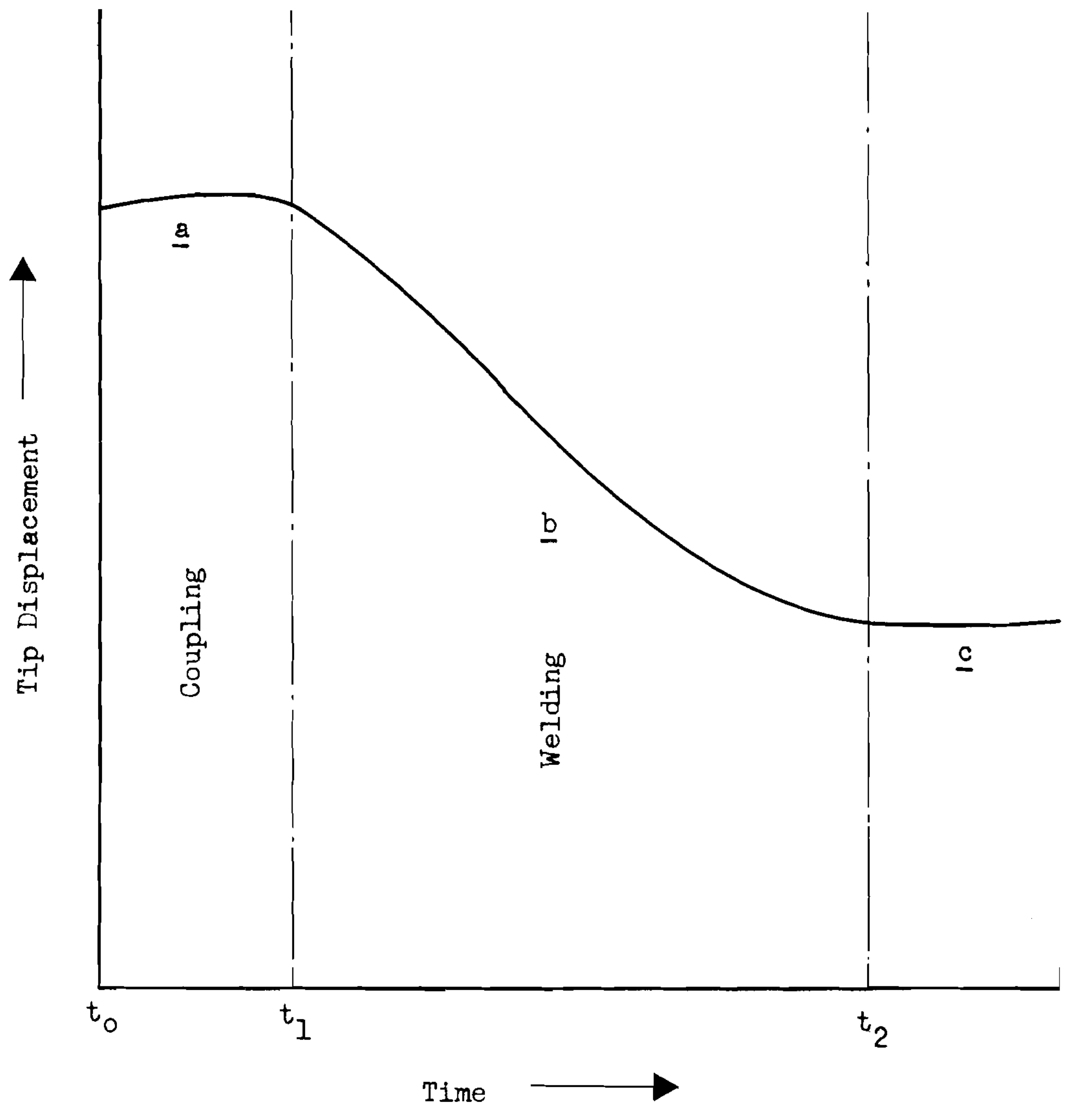

Figure 2

TYPICAL PATTERN OF WELDING TIP DISPLACEMENT
AS A FUNCTION OF TIME
FOR ACHIEVING EFFECTIVE BONDS

After the tip-workpiece coupling has been established (at time t_1), the tip displacement begins to decline and continues to do so as the weld is formed. The decline in tip displacement tapers off possibly as the weld area increases or the bond becomes stronger until time t_2, when the weld is apparently completed. Any extension of time beyond t_2 is seemingly useless and probably damages the weldment.

Control over weld time, defined by the slope of the displacement curve, has been successfully used on production ultrasonic welding machines by the General Electric Company, Hanford Atomic Products Operation (16), the tip displacement being sensed with a phonograph pickup mounted on one side of the tip.

The tip displacement pattern shown in Figure 2 was confirmed using samples of 0.040-inch 2024-T3 aluminum alloy and 0.025-inch Type 302 stainless steel, which are relatively easy to weld. Typical curves obtained with the aluminum alloy are shown in Figure 3. The first plot follows the pattern described above. In the second instance, the interface coupling process begins as power is applied; this pattern is also characteristic of the type obtained with the stainless steel. Curves of both Types A and B have been obtained with aluminum alloy specimens that exhibited tensile-shear strengths in the range of 800-1200 pounds. On the other hand, curves of Type C, in which tip displacement shows little variation throughout the weld cycle, are typical of low-strength welds in this material (below 800 pounds).

C. WELD STRENGTH EVALUATION

1. Weld Peel Tests

To evaluate strength of weldments by this method, welds are manually peeled and the fractured surfaces examined. If the weld is sound, a nugget will be pulled completely out of one sheet; a moderate weld will exhibit a partial nugget on peeling; and some adhesion or no adhesion indicates an incomplete (partial) or no bond, respectively. This method for testing strength, which is visual only, proves valuable only when the materials being welded are reasonably ductile. In peeling brittle materials, cracks are frequently produced and these otherwise nullify the results.

2. Tensile-Shear Tests

For an accurate measurement of the actual strengths of welds, tensile-shear tests were conducted using an Instron Model TT-C-L testing machine.

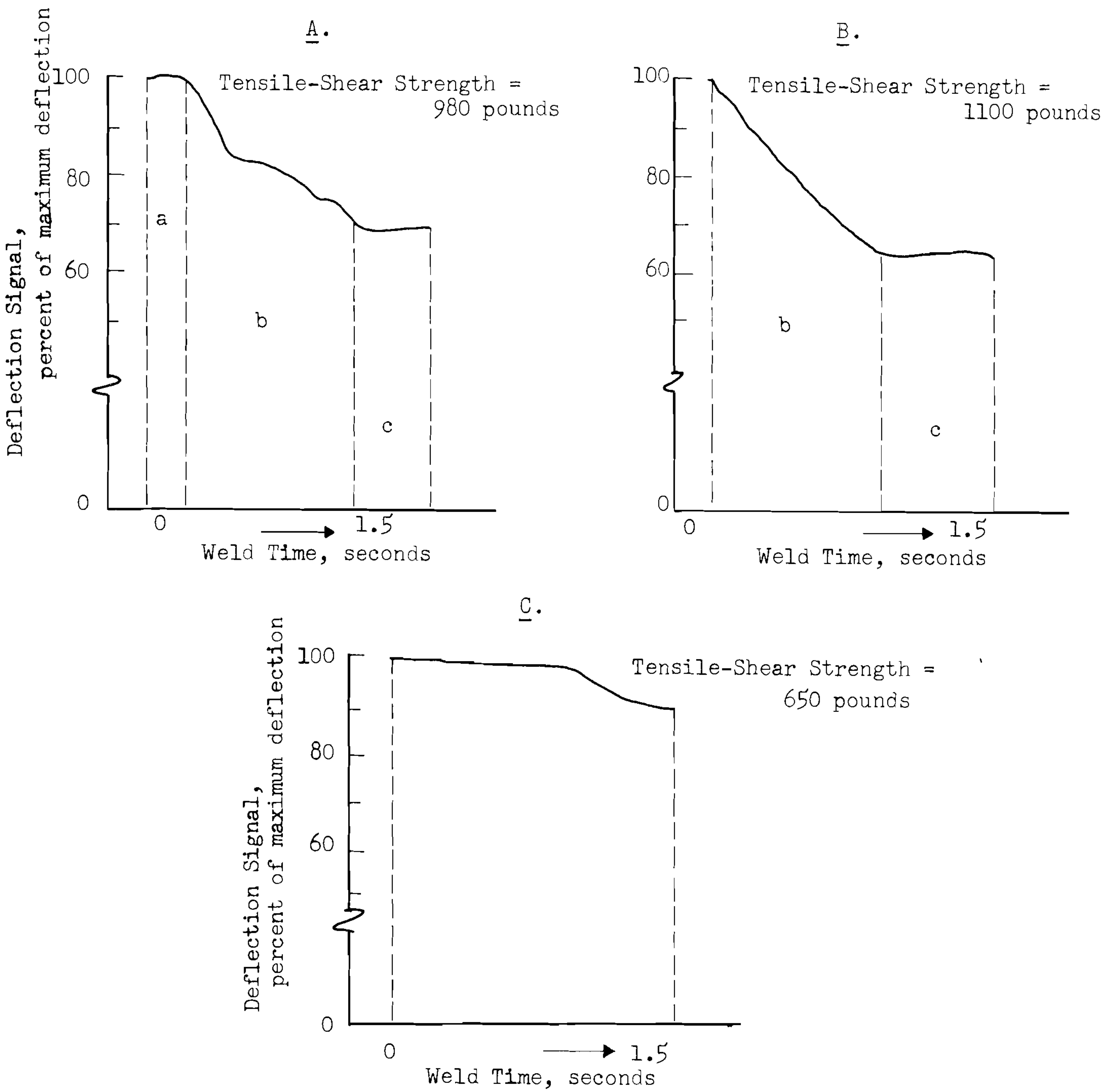

Figure 3

TYPICAL WELDING TIP DEFLECTION SIGNAL RECORDINGS
FOR 0.040-INCH 2024-T3 ALUMINUM ALLOY

3. Statistical Analysis of Data

When significant strength data were obtained from a number of samples, the results were analyzed statistically to determine the average strength and the standard deviation. In some instances the expected minimum (the average value minus three times the standard deviation) was also calculated.

D. METALLURGICAL EVALUATIONS

To determine weld quality, degree of bonding, existence of cracks, deformation, and other factors, specimens were subjected to metallurgical study. Extensive metallurgical testing is prohibitive where large quantities of specimens are involved.

1. Visual Examination

Visual examination of the weld surfaces is a convenient method for obtaining a limited amount of information relative to weld quality. A steroscopic microscope was used to examine the surface of the weld specimen contacted by the welding tip, the surface contacted by the anvil, and the interfaces of sheared specimens. It was thus possible to determine the bond envelope area, a qualitative indication of the bonding between the workpieces, the discoloration indicative of high temperatures achieved during welding, and the presence of gross cracks extending to the surface. Such examination, however, may not reveal surface microcracks, and it does not reveal internal cracks nor the effect of welding on the metallurgical structure of the metal.

2. Cross Sectioning for Microexamination

This technique consists of cross-sectioning welded joints at a 90-degree angle parallel to and normal to the direction of tip vibration, to determine the shape and depth of any cracks in relation to weldment thickness. The nature and cause of cracks are also indicated upon examination of a cross section.

Specimens are examined both before and after etching. The soundness or extent of the weld may be indicated before etching. Prolonged etching, however, may exaggerate the dimensions of the bond line, especially with bimetallic welds, because of the rapid interfacial attack of reagents.

In preparing the specimens for metallographic examination, the following etchants were used:

1. A 50:50 mixture of 10% aqueous potassium hydroxide solution and 10% aqueous potassium ferric cyanide solution (used for molybdenum alloy specimen in Figure 10).

2. A 50:50 mixture of 10% aqueous sodium hydroxide solution and 10% potassium ferric cyanide solution (used for molybdenum alloy specimens in Figures 17, 18, and 32 and for tungsten specimen in Figure 36).

3. An aqueous solution containing 50 parts lactic acid, 30 parts nitric acid, and 10 parts hydrofluoric acid (used for molybdenum alloy specimens in Figures 12-16 and 19, for D-31 alloy specimens in Figures 20, 24-29, and 34, and for tungsten specimen in Figure 30).

3. Planar Sectioning

As noted above, cross sectioning involves cutting through the weldment at a 90-degree angle to the weld interface, either parallel or normal to the direction of tip vibration. Planar sectioning involves successively removing material from the weldment in planes parallel to the weld interface. It may reveal cracks and tears in a weldment that are not evident in cross sections, and provides a more reliable indication of overall weld integrity.

Planar sectioning was used on a limited number of specimens, a minimum of four planar sections being exposed on each weldment. The process, however, is time consuming and is difficult to accomplish on weldments in thin-gage sheet, which may be warped or easily dislodged from the mounting medium.

E. NONDESTRUCTIVE TESTING TECHNIQUES

Inasmuch as cracking of the weld metal was a problem encountered in the ultrasonic welding of the refractory metals (some of which proved to be contaminated) incident to this program, it became apparent that development of the process required an improved means for detecting such internal flaws. To be practical, such inspection should be reliable, inexpensive, and of a nondestructive nature. It should also be capable of detecting unbonded areas, as well as other defects in the weld area. Consideration was therefore given to available techniques of nondestructive testing and their potential for evaluating ultrasonic welds in thin refractory metal sheet.

1. X-Ray Inspection

This technique, although not fast or inexpensive, has frequently been used for study of welds produced by other processes. However, relatively fine cracks in the metal are exhibited on X-ray film only if the cracks are parallel to the X-ray beam; otherwise, cracks must have considerable thickness to produce an image. Furthermore, the image may be inhibited by variation of metal thickness in the area of the flaw. Instances have been encountered in which a crack visible to the naked eye was not observed even by highly trained X-ray examiners (17).

2. Penetrant Inspection

It was decided to experiment briefly with a supersensitive fluorescent penetrant, Super-Penetrex ZL-22*; a number of welds in 0.005-inch and 0.010-inch molybdenum-0.5% titanium alloy were inspected by this technique. It was effective only for detecting gross cracks extending to the outer surfaces of the weldment.

3. Temperature-Indicating Liquids

In this technique, a substance with a known melting point, suspended in an inert, volatile liquid, is spread over the surface of the area containing potential cracks. With the application of concentrated heat to the reverse side of the sheet, the volatile vehicle evaporates, leaving the suspended solid on the surface. During melting of the solid, any discontinuities such as cracks and voids disturb the heat flow so that a pattern correlating with the internal and external flaws is produced.

TEMPILAQ,** a temperature indicating coating, was used for detection of internal flaws in 0.005- and 0.010-inch molybdenum-0.5% titanium alloy sheets. Although a pattern was produced, surface roughness interfered with evaluation; subsequent grinding brought no better results. This method was discontinued as too insensitive for this application.

4. Infrared Radiometry

Infrared radiometry*** is a technique wherein the thermal radiation from areas is precisely sensed and otherwise displayed so as to indicate surface temperature gradients. Properly applied heat makes it possible to detect internal flaws immediately. Lack of adequate funds precluded experimental investigation of this method.

5. Ultrasonic Inspection

Various ultrasonic techniques applicable to crack detection were examined, but none appeared usable in its present state of development. Transverse or shear waves, commonly used for flaw detection, are ineffective unless the specimen thickness is at least one wavelength. The immersion method occasions too great an ultrasonic energy loss by reflection at the water/metal interface. Surface or Lamb waves showed promise in preliminary tests**** but would require extensive equipment modification and calibration for reliable use with thin sheets. The point-contact transducer method under development at Watertown Arsenal Laboratories (19) presently appears the most promising technique.

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* Developed by Magnaflux Corporation
**Manufactured by Tempil Corporation, New York, N.Y.
***Developed and marketed by Barnes Engineering Company, Stamford, Conn.
****Conducted by Sperry Products Company, Danbury, Conn.

V. WELDING OF MOLYBDENUM-0.5% TITANIUM ALLOY

A major portion of the effort was devoted to welding thin gages of the molybdenum-0.5% titanium alloy. This resulted from substantial inconsistencies in the quality of the sheet material which became evident as the work progressed. Machine settings that appeared adequate for one piece of material would sometimes fail to produce any welds in other material or would cause major cracking in still other pieces. Various methods for delineating machine settings were utilized during observations of erratic welding behavior.

A. EXPERIMENTS WITH LOT 1 MATERIAL

Initial experiments were carried out with residual pieces of 0.006- and 0.011-inch molybdenum-0.5% titanium alloy sheet which were previously acquired samples. Of unknown history, this material was a powder metallurgy product and was laminar in character, as observed during shearing of the test coupons, sharp bending, and peeling of the weldments. The material was somewhat softer than the hot-rolled, arc-cast material used later in the program; the DPH of the 0.006-inch material was 230, and that of the 0.011-inch material was 260 (compared with hardnesses generally ranging from 275 to 305 DPH for Lots 2, 3, and 4 (Table II)). Hence, the calculated energy requirements were less than those indicated by the curves of Figure 1: approximately 500 watt-seconds for the 0.006-inch gage and 1525 watt-seconds for the 0.011-inch gage.

1. Clamping Forces Approximated From Peel-Test Threshold Curves

Specimens of each of the above gages welded with preselected combinations of power and clamping force were evaluated by the manual peel test. The resulting data permitted construction of the energy-clamping force curves depicted in Figure 4, A and B. Based on this evaluation, the minimum energy condition for nugget welds in the 0.006-inch material was indicated at an energy level of 475 watt-seconds and a clamping force in the range of 300-400 pounds. For the 0.011-inch material, the minimum energy condition was found to be approximately 725 watt-seconds (considerably lower than computed with the energy equation) at a clamping force also in the range of 300-400 pounds. Subsequent work indicated these values to be low.

2. Clamping Force Approximated From Temperature Rise

In order to verify the data obtained above, coupons of 0.011-inch material were used to measure the temperature rise in the weld zone as previously described. Specimens were welded at the approximate minimum energy condition indicated by the threshold curves: 1200 watts for 0.6 second, or

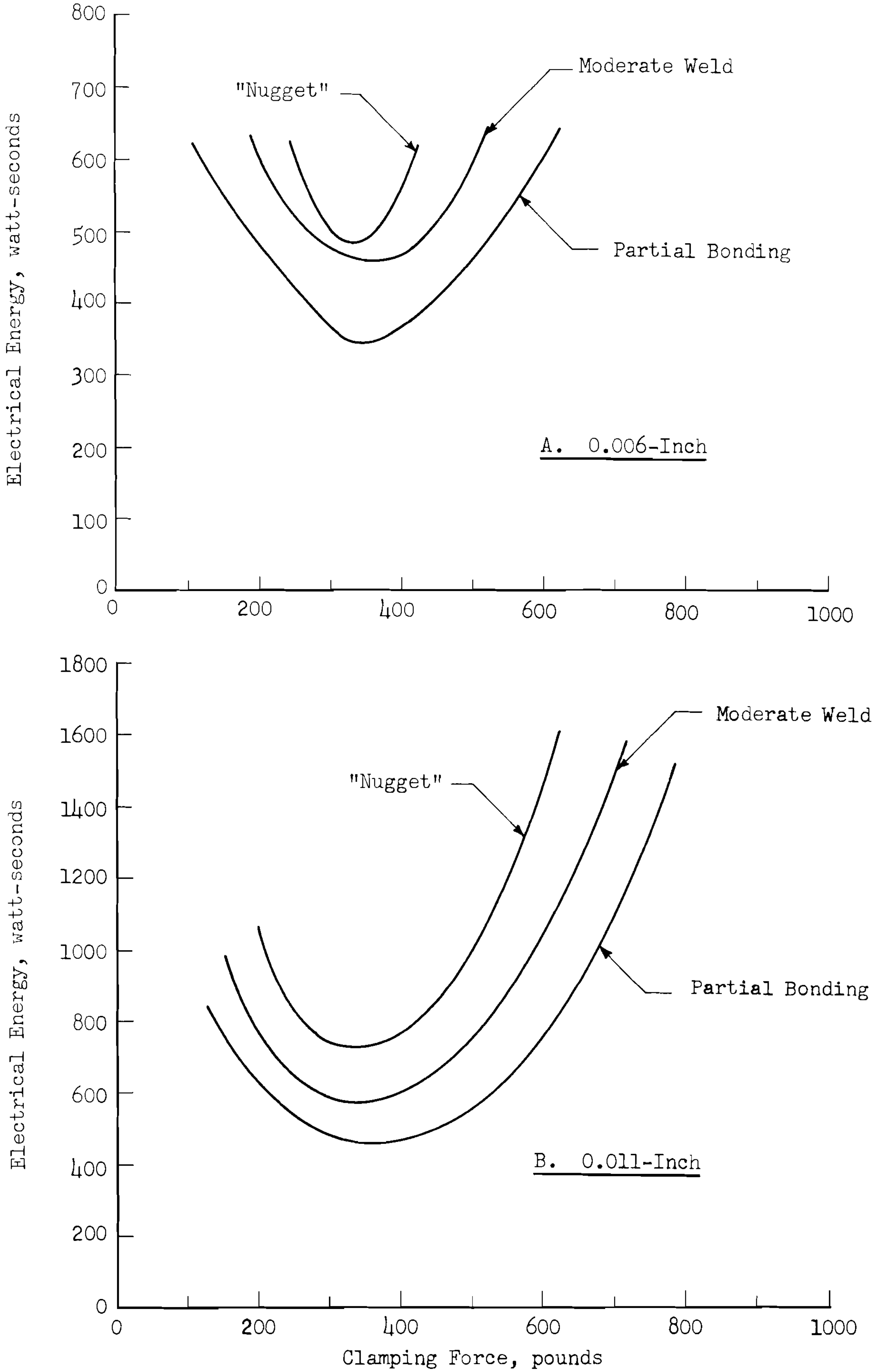


Figure 4

THRESHOLD CURVES OF ENERGY VS. CLAMPING FORCE
FOR WELDING TWO GAGES OF MOLYBDENUM-0.5% TITANIUM ALLOY (LOT 1)

720 watt-seconds; clamping force was varied from 325 to 700 pounds. (The 375-pound figure was the lowest that could be measured accurately with the welder used. The welder was later modified to accommodate any clamping force within the range of 50 to 1000 pounds.)

Various of the specimens exhibited erratic temperature rise traces due in part to the tendency of the material to delaminate. Only those readings were considered valid which exhibited smooth rise and decay curves as illustrated by the sample traces in Figure 5.

The measured temperature rise is plotted as a function of clamping force in Figure 6. These data appear to confirm the results obtained with the peel tests, that the optimum clamping force is in the range of 300-400 pounds.

B. INITIAL EXPERIMENTS WITH LOT 2 MATERIAL

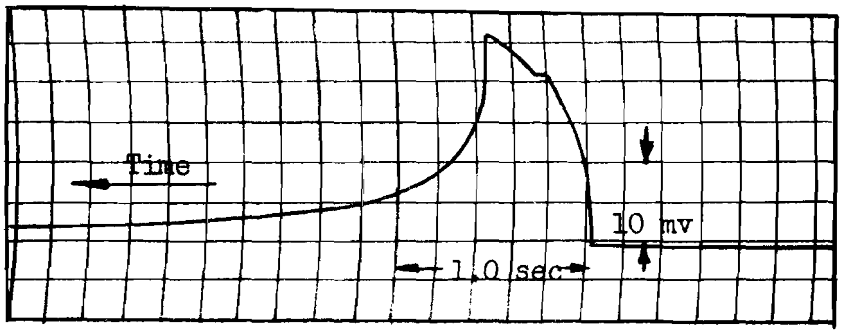
Subsequent experiments were carried out with molybdenum-0.5% titanium alloy sheet which had been hot-rolled from arc-cast ingots, stress relieved, and descaled. As noted in Table II, the composition and mechanical properties of this material lot (especially hardness) exhibited considerable variation, even among individual pieces of the same gage.

The experimental work was performed chiefly with the 0.005 and 0.010 gage which, according to Table VI, should require approximately 500 and 1450 watt-seconds of energy respectively for welding.

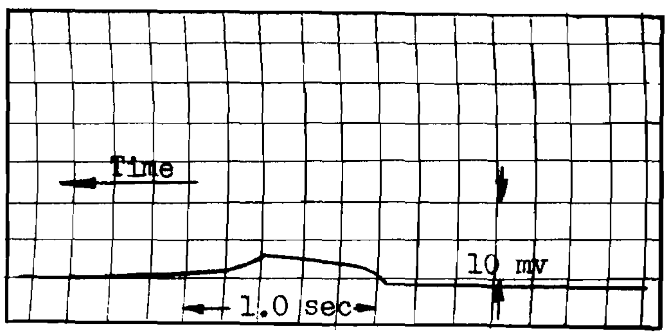
1. Threshold Curves for Approximation of Clamping Force

To construct threshold curves for the 0.005-inch material, welds were made at a weld time of 0.6 second, at power levels of 800, 1000, 1200, and 1400 watts (energy levels of 480, 600, 720, and 840 watt-seconds), and at clamping forces covering the range from 100 to 700 pounds. The proper clamping force was found to be in the range of 300 to 500 pounds, and the minimum power at this clamping force was 1000 watts (600 watt-seconds). This is somewhat higher than the minimum power for the 0.006-inch powder-metallurgy Lot 1 material (475 watt-seconds), as would be expected from the higher hardness.

The 0.010-inch material was welded at the same time, 0.6 second, at the higher powers of 1000, 1500, 2000, and 2500 watts (600, 900, 1200, and 1500 watt-seconds), and at clamping forces ranging from 100 to 800 pounds. At these power levels, the weldments did not peel complete nuggets; the separation was a partial nugget corresponding to the "moderate weld" described on page 18. This may be an indication of better cross-laminar strength of the arc-cast material, rather than being indicative of weld quality inferior to that obtained in the powder metallurgy product.



375-lb Clamping Force



700-lb Clamping Force

Figure 5

TYPICAL TEMPERATURE TRACES OBTAINED DURING WELDING OF 0.011-INCH MOLYBDENUM-0.5% TITANIUM ALLOY

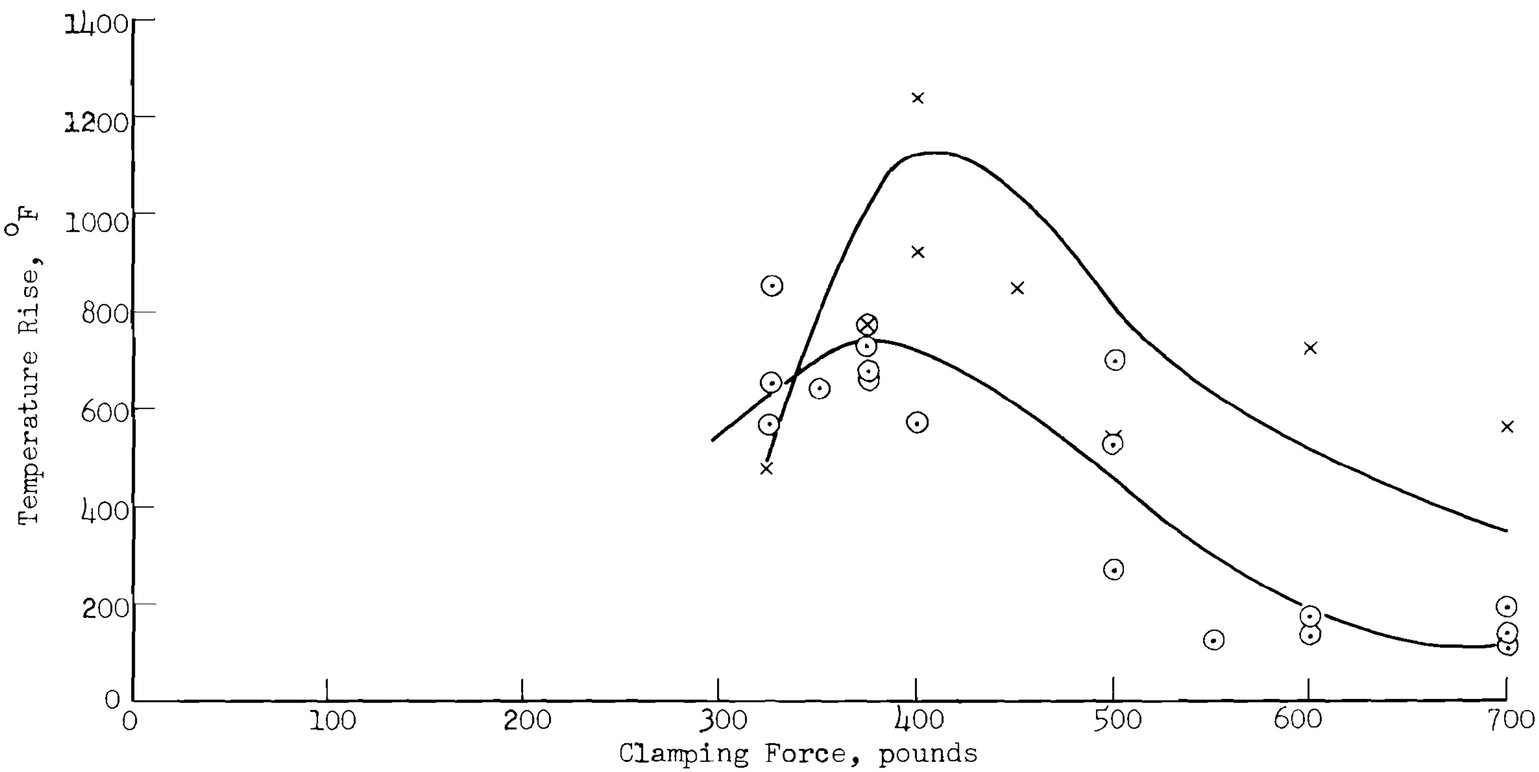


Figure 6

TEMPERATURE RISE IN WELD ZONE AS A FUNCTION OF CLAMPING FORCE
DURING WELDING OF 0.011-INCH MOLYBDENUM-0.5% TITANIUM ALLOY

× First weld pulse on a specimen
⊙ Pulse subsequent to initial weld (clamping force not removed)

The minimum energy required for these "moderate welds," as determined by the threshold curves, was 600 watt-seconds at a clamping force of 400 pounds. Unlike the 0.011-inch powder metallurgy alloy (Figure 4B), this threshold curve rose sharply when the clamping force was varied by only 100 pounds in either direction from 400 pounds. It should be emphasized that, in view of the type of peel fracture, the above minimum energy condition for the 0.010-inch material was not expected to be the one which produces the best welds; rather it established the approximate optimum clamping force, and thus furnished a basis for experiments with various combinations of power and weld time at energy levels somewhat higher than the minimum.

2. SWR Ellipse Area for Approximation of Clamping Force

Further work by means of the SWR technique indicated the optimum clamping force. Welds were produced at a single power and weld time with several values of clamping force. The results obtained for the 0.005-inch material, shown in Figure 7, indicate 300 pounds as the proper clamping force. Similar data for the 0.010-inch material indicate 400 pounds as the proper clamping force.

3. Welding Tip Displacement

Tip displacement patterns during welding of the 0.005-inch molybdenum alloy were obtained at a clamping force of 300 pounds, input power of 1200 watts, and weld time of 0.6 second. Typical curves are presented in Figure 8.

The curve for Specimen A indicates that coupling was delayed until the last 0.1 second of the weld time, and the specimen was not bonded. After an initial pre-coupling period, Specimen B absorbed energy at a rapid rate and formed a bond. Specimen C, which demonstrated a relatively high tensile-shear strength, absorbed energy in a gradual manner.

4. Strength

No effort was made to evaluate weld quality of the foregoing other than by the manual peel test. Subsequent work considered the effect of variation in welding machine settings on weld tensile-shear strength. For the 0.005-inch material, clamping force was varied from 300 to 700 pounds, power from 1000 to 2500 watts, weld time from 0.3 to 1.0 second, and input energy from 400 to 2500 watt-seconds. The 0.010-inch material was welded at power levels from 1800 to 3000 watts, clamping forces of 350 and 400 pounds, and weld times from 0.5 to 1.0 second. The welded specimens were tested in tensile-shear, and the sheared interfaces were examined.

The results, presented in Table VII, show a variation in individual weld strengths. The best results for the 0.005-inch gage appeared to be within the range of 560 to 720 watt-seconds, and 300 pounds clamping force was superior to 600 pounds. For the 0.010-inch material, the results were so sidely scattered as to be inconclusive.

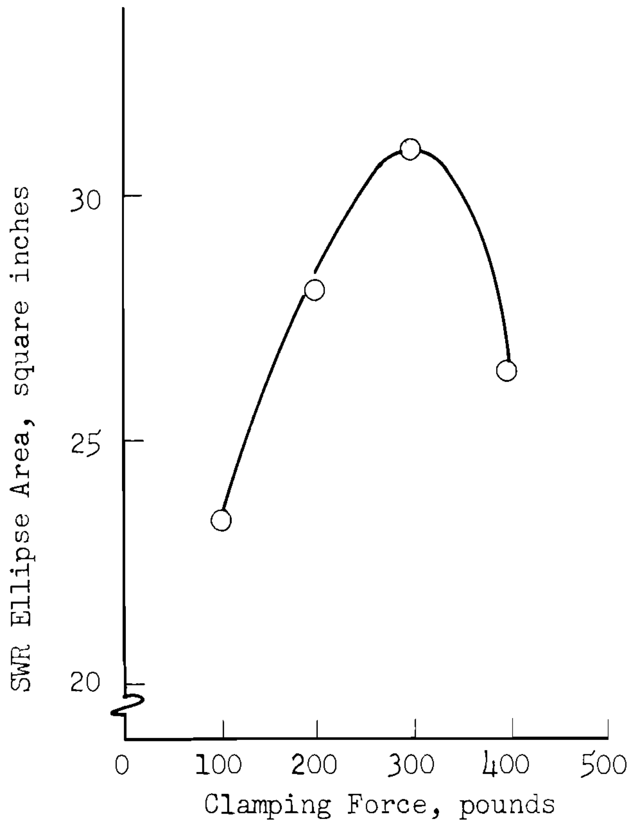


Figure 7

CURVE OF SWR ELLIPSE AREA VS. CLAMPING FORCE
FOR 0.005-INCH MOLYBDENUM-0.5% TITANIUM ALLOY

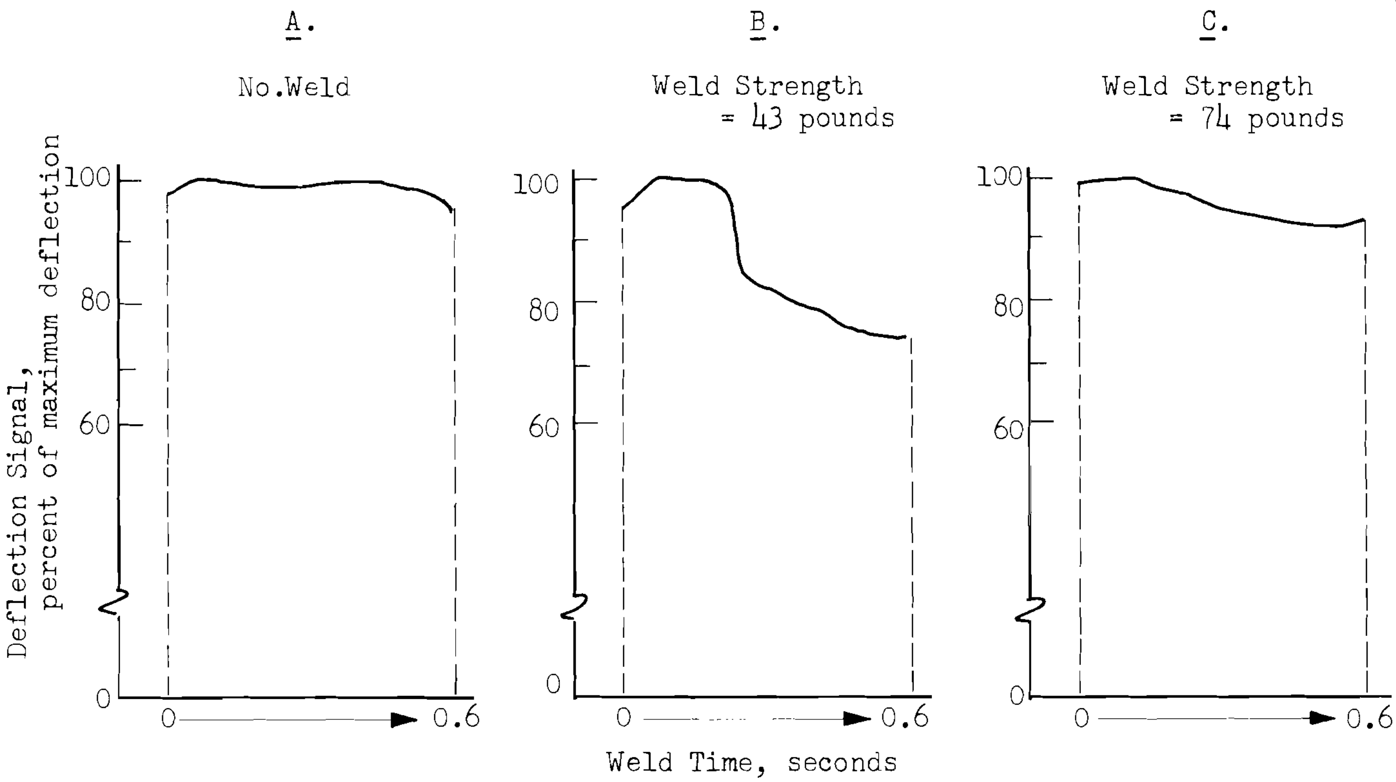


Figure 8

WELDING TIP DEFLECTION SIGNAL RECORDINGS
FOR 0.005-INCH MOLYBDENUM-0.5% TITANIUM ALLOY

Input Power: 1200 watts
Clamping Force: 300 pounds

Table VII

EFFECT OF WELDING CONDITIONS ON TENSILE-SHEAR STRENGTH
OF ULTRASONIC WELDS IN 0.005-INCH AND 0.010-INCH MOLYBDENUM-0.5% TITANIUM ALLOY

Welding Conditions					Tensile-Shear Strength		
Energy, watt-sec	Power, watts	Clamping Force, pounds	Weld Time, second	No. of Specimens	Average, pounds	Range, pounds	Standard Deviation, pounds
				0.005-Inch Gage			
400	1000	300	0.4	2	24	23	
400	1000	600	0.4	2	34	22	
560	1400	300	0.4	2	55	0	
560	1400	600	0.4	2	50	6	
720	1200	300	0.6	6	60		25
720	1200	600	0.6	10	42		8
800	1000	300	0.8	2	34	22	
800	1000	600	0.8	2	31	30	
1120	1400	300	0.8	2	41	17	
1120	1400	600	0.8	2	47	11	
1184	1400	350	0.74	15	50		11
2500	2500	700	1.0	4	58		50
				0.010-Inch Gage			
1080	1800	350	0.6	6	60		20
1080	1800	400	0.6	6	77		30
1800	3000	400	0.6	6	62		14
2400	3000	400	0.8	6	64		25
3000	3000	400	1.0	6	51		30
1800	3600	400	0.5	3	54		19
2880	3600	400	0.8	3	74		28

Few of the specimens in either gage failed by complete nugget tear-out. Some of the welds appeared sound and crack-free, while others contained cracks. Some of these cracks apparently developed as a result of the shear stresses applied during testing; others were obviously concomitant of welding. No single set of conditions utilized produced consistently sound, crack-free welds.

The sheared interfaces of these weldments showed varying patterns such as the two shown in Figure 9. In some instances, the spot welds assumed the annular configuration of Figure 9A. Most of the specimens, however, demonstrated the weld pattern of Figure 9B, in which the bonded regions were randomly distributed within the envelope area.

In spite of the tendency toward cracking and the random bonding demonstrated by this molybdenum alloy, limited metallurgical studies during this early work showed that bond locales had excellent quality. In the photomicrograph of Figure 10, for example, the bond is good and of uniform quality over the entire section. Considerable internal displacement has occurred at the weld interface, to the extent that the initial contacting surfaces are obliterated. There is no evidence of recrystallization in the area of plastic flow. Thus the material clearly has good metallurgical susceptibility to joining by ultrasonic welding.

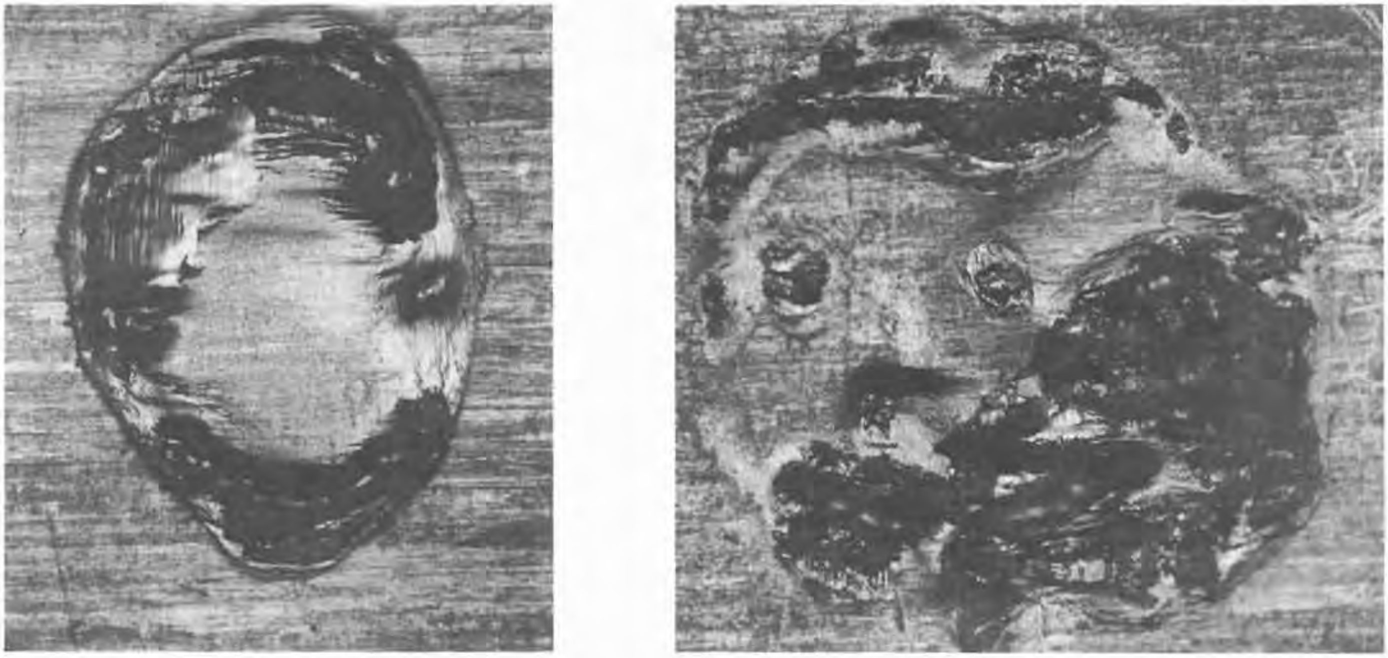
C. EFFORTS TO IMPROVE WELDABILITY

Consideration was given to several possible means which should operate to facilitate plastic flow and inhibit the cracking tendency in this molybdenum alloy.

1. Biaxial Restraint

Welding should be facilitated if the tip element geometries could maintain the entire welding locale in compression. With a flat anvil face the tip of a wedge-reed system excursions in an arc, and the clamping force is relieved somewhat at the excursion extremes, so that optimum welding conditions do not prevail at these extremes. To explore this condition, a few welds were made with the concave anvil described in Section III, the concavity matching the estimated arc radius described by the tip during displacement. Coupons of 0.005-inch molybdenum-0.5% titanium alloy were welded at a clamping force of 300 pounds, power of 1200 watts, and weld time of 0.6 second (conditions which approximated the optimum for this material), using both flat and concave anvil faces. The results of tensile-shear tests on these weldments were as follows:

Anvil Face	No. of Specimens	Average Tensile-Shear Strength, pounds	Standard Deviation, pounds
Flat	22	56	17
Concave	12	57	10



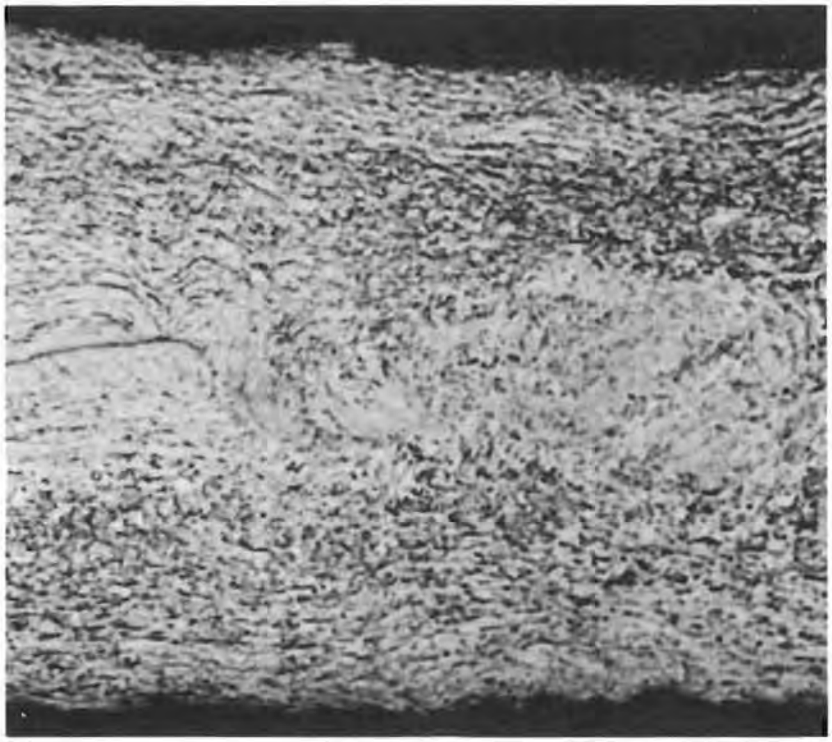
A. Annular Weld Area Characteristic of Ultrasonic Bonds

B. Random Distribution of Bonded Areas In Weld Envelope

Figure 9

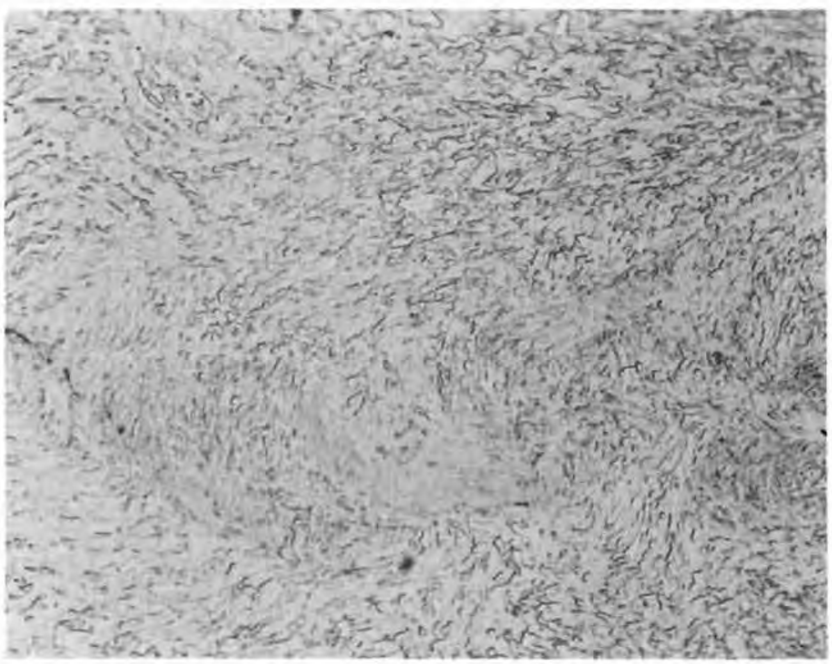
TYPES OF WELD ENVELOPE PATTERNS
FORMED IN 0.005-INCH MOLYBDENUM-0.5% TITANIUM ALLOY

Interface



A. Magnification: 200X

Interface



B. Magnification: 500X (portion of A. area)

Figure 10

PHOTOMICROGRAPHS OF ULTRASONIC WELD
IN 0.005-INCH MOLYBDENUM-0.5% TITANIUM ALLOY

Power: 1100 watts
Clamping Force: 350 pounds
Weld Time: 0.6 second

The difference in the average strengths is obviously not significant, but the decreased variability of the data for the concave tip, expressed in terms of the standard deviation, indicates appreciable improvement in reproducibility for welds made with this concave tip.

Clearly a spherical tip and a concave anvil combination is impractical, but maintenance of the weldment locale in compression may also be accomplished with force programming. It should be noted that other types of sonotrode systems differ from the wedge-reed sonotrode system and that the relief of compressive stress associated with the excursion extremes of the wedge-reed system can, in practice, be avoided without resort to a concave anvil.

2. Reduce Number of Stress Cycles

It was further considered that fatigue cracking, if such is the mechanism, could be prevented by decreasing the number of stress cycles to which the material is subjected during ultrasonic welding, i.e., reducing the weld time.

Welds were produced in the 0.005-inch material at a clamping force of 300 pounds and with a total weld energy of 720 watt-seconds. For one group of specimens, power of 1200 watts was applied for 0.6 second, and for another group 2400 watts were applied for 0.3 second. The tensile-shear values were as follows:

Weld Time, second	Applied Power, watts	No. of Specimens	Average Tensile-Shear Strength, pounds	Standard Deviation, pounds
0.6	1200	6	60	26
0.3	2400	5	58	12

The shorter weld time produced lower variability and thus appeared to be more effective.

3. Modification of Surface Treatment

The inconsistencies in welding this material, and particularly the appearance of the random bonding illustrated in Figure 9B, suggested improvement via improved surface finish. Polishing or etching should therefore permit more intimate and uniform contact between the sheets and result in improved quality bonds.

Three sets of eight specimens each were welded under identical machine settings. Prior to welding, the first set was degreased with

Pennsalt A-27 detergent solution; the second set was prepared for welding by electropolishing as described in Section IV; and the third set was degreased in a detergent solution and welded with the concave rather than the flat-faced anvil. Welds were made at a clamping force of 300 pounds, at energy levels of 480, 600, 720, and 840 watt-seconds, and at weld times of 0.3 and 0.6 second.

The following tensile-shear results were obtained at 1200 watts power and 0.6 second weld time:

Surface Treatment	Anvil	No. of Specimens	Average Tensile-Shear Strength, pounds	Standard Deviation, pounds
Degreased	Flat	4	64	22
Electropolished	Flat	4	60	8
Degreased	Concave	4	50	16

The difference in average strength is not significant, in view of the small number of specimens. However, the decreased variability with the electropolished specimens indicates that either the improved surface or the elimination of surface contamination, or both, contribute noticeably to the quality of the welds.

4. Welding with Foil Interleaf

In prior work, an interleaf of thin foil interposed between the sheets to be joined successfully increased weld strength and reduced susceptibility to cracking, and this technique was investigated with the 0.005-inch molybdenum alloy. In order to retain the effective high-temperature properties of the parent material, it is essential that the foil interleaf also exhibit good high-temperature characteristics. Consequently, one foil interleaf used was 0.0005-inch tantalum. Other weldments were made using 0.0005-inch titanium (ASM 4910-B) foil interleaves because, under certain circumstances, this material performs well for short periods at high temperatures.

Three groups of 0.005-inch alloy specimens were prepared, using welding conditions of 1000 watts power, 300 pounds clamping force, and 0.6 second weld time. Time did not permit an extensive study of welding machine settings, and the values used were the same as for non-interleaf specimens. One group was welded without interleaf to serve as controls, a second group was welded with the 0.0005-inch titanium foil interleaf, and the third group with the 0.0005-inch tantalum foil interleaf. Results were as follows:

Interleaf Material	No. of Specimens	Average Tensile-Shear Strength, pounds	Standard Deviation, pounds
None	10	45	17
0.0005" Titanium	7	42	9
0.0005" Tantalum	8	43	9

It will be noted that the average tensile-shear strengths of the three groups were essentially the same, but the variability was substantially less for the specimens welded with interleaves than for the non- interleaf welds.

Additional specimens of each of the three types were welded with the same clamping force and weld time, but with the power increased to 1200 watts. One of each type was examined by the planar sectioning method. The top sheet of the titanium interleaf specimen was free from flaws, but the bottom sheet of this specimen, as well as the top sheet of the control specimen, and both top and bottom sheets of the tantalum interleaf specimen, exhibited internal discontinuities. In the light of the reduced standard deviation, this work should be extended to include a comprehensive study of machine settings.

5. Refinement of Testing Procedure

The variability in strength, as well as the incidence and types of cracks encountered in the sheared specimens, suggested that the testing procedure might require improvement to accommodate the hard refractory materials. It had been noted that the grips of the steel-faced jaws of the Instron testing machine required very careful adjustment to hold the specimens securely.

The effects of (a) increased specimen size to provide a greater area of contact with the testing machine jaws, and (b) insertion of emery paper between the jaws and the specimen to minimize slippage during load application were considered. In all cases, care was taken to insure alignment of the specimen in the testing machine. Weldments were prepared in 0.005-inch and 0.010-inch molybdenum-0.5% titanium alloy using coupons 1/2 by 2 inches and 3/4 by 3 inches. The 0.005-inch material was welded at 1200 watts power, 300 pounds clamping force, and 0.6 second weld time. The 0.010-inch material was welded at 3000 watts power, 4000 pounds clamping force, and 0.8 second weld time.

The results, presented in Table VIII, show the anticipated results. Within this group of specimens, there was a clear trend toward increased weld strength, both with increased specimen size and with the use of the abrasive lining on the test jaws. In addition, there was a decrease in strength variability when care was thus taken to minimize slippage. While these differences may not be statistically significant, due to the limited number of specimens, there appears little doubt that the testing technique is important.

D. WELDING OF LOTS 3 AND 4 MOLYBDENUM ALLOY

The previous work had shown that molybdenum-0.5% titanium alloy demonstrated metallurgical characteristics conducive to good ultrasonic welding. However, the variability of weld strength and the occasional cracking tendency indicated unrecognized problems.

A comprehensive literature survey concerning this alloy was undertaken, and direct inquireies were made to persons and companies known to have appropriate experience with this material. In addition, the earlier work was re-analyzed in an attempt to isolate and resolve problems pertaining to its propensity to crack under certain ultrasonic welding conditions. On the basis of these considerations, a new series of studies was executed, and the results were analyzed in terms of strength and metallography. This work was carried out with the materials designated as Lots 3 and 4 in Table II.

The effect of welding tip radius on material weldability was reconsidered, as described in Section III, and weldments in this new series were made using tip radii within the range from 50 to 100 times the sheet thickeness, i.e., radii of 0.25 and 0.50 inch for the 0.005-inch material, and radii of 0.50 and 0.75 inch for the 0.010-inch material.

1. Strength

Table IX summarizes the results of tensile-shear tests on these materials. As will be noted, the 0.0055-inch material of Lot 3 showed low and variable strengths. Subsequent metallographic examination, described below, revealed a high incidence of cracks.

The 0.008-inch material of Lot 3 did not respond to ultrasonic welding. Efforts were made to establish satisfactory welding machine settings. Of the 43 specimens in which welding was attempted, only 13 were welded, and the tensile-shear strengths of these ranged from 15 to 103 pounds. The remainder either did not weld at all or cracked severely during welding. Typical cracks produced during welding are shown in Figure 11. This material had been ordered in the annealed state, but metallographic examination showed it to be fully recrystallized (see Figure 12), although the surfaces were free from contamination. The material

Table VIII

EFFECT OF SPECIMEN SIZE AND TESTING PROCEDURE
ON STRENGTH OF ULTRASONIC WELDS IN MOLYBDENUM-0.5% TITANIUM ALLOY

			Welding Conditions				Tensile-Shear Strength	
Sheet Gage, inch	Coupon Size, inches	Specimen Gripping Method	Power Power, watts	Clamping Force, pounds	Weld Time, seconds	No. of Specimens	Average, pounds	Standard Deviation, pounds
0.005	3/4 x 3	Steel Jaws	1200	300	0.6	3	29	15
	3/4 x 3	Abrasive*	1200	300	0.6	22	46	11
0.010	1/2 x 2	Steel Jaws	3000	400	0.8	6	64	27
	1/2 x 2	Abrasive*	3000	400	0.8	5	85	18
	3/4 x 3	Abrasive*	3000	400	0.8	5	103	26

* Abrasive inserted between test jaws and specimen.

Table IX

STRENGTHS OF ULTRASONIC WELDS
IN LOTS 3 AND 4 MOLYBDENUM-0.5% TITANIUM ALLOY

Material	Sheet Gage, inch	Welding Tip Radius, inch	Welding Machine Settings: Power, watts	Welding Machine Settings: Clamping Force, pounds	Welding Machine Settings: Weld Time, seconds	No. of Specimens	Tensile-Shear Strength: Average, pounds	Tensile-Shear Strength: Standard Deviation, pounds	Tensile-Shear Strength: Expected Minimum, pounds
Lot 3	0.0055	0.25	1100	400	0.5	27	26	18	-28
Lot 3	0.0055	0.50	1400	700	0.5	13	48	23	-21
Lot 3	0.008	0.75	2400-3200	500-1000	0.3-0.5	43	*		
Lot 4	0.010	0.50	2900	1000	0.5	23	122	41	-1
Lot 4	0.010	0.75	3000	1000	0.5	21	179	23	110

* Of 43 weldments attempted, only 13 were actually bonded; tensile-shear strengths ranged from 15 to 103 pounds.

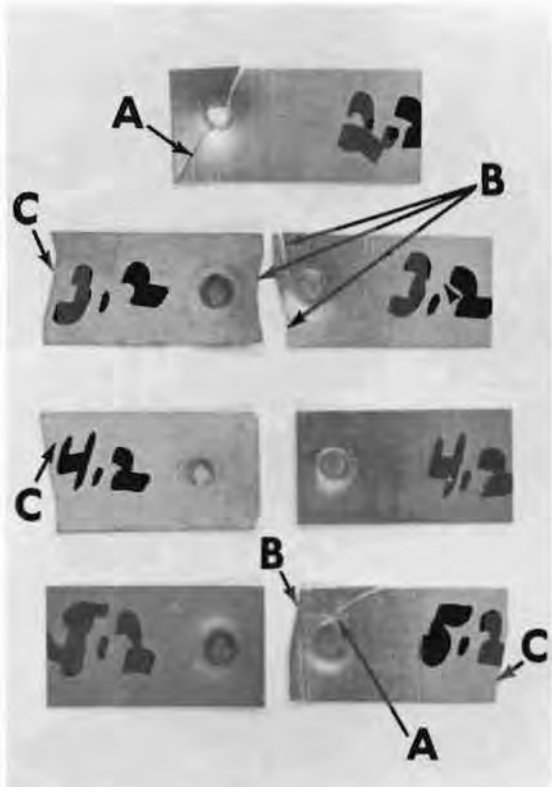


Figure 11

ULTRASONIC WELDS IN 0.008-INCH MOLYBDENUM-0.5% TITANIUM ALLOY
CRACKED DURING WELDING

Note shattered material: A. In welds
B. Close to welds
C. Far from welds

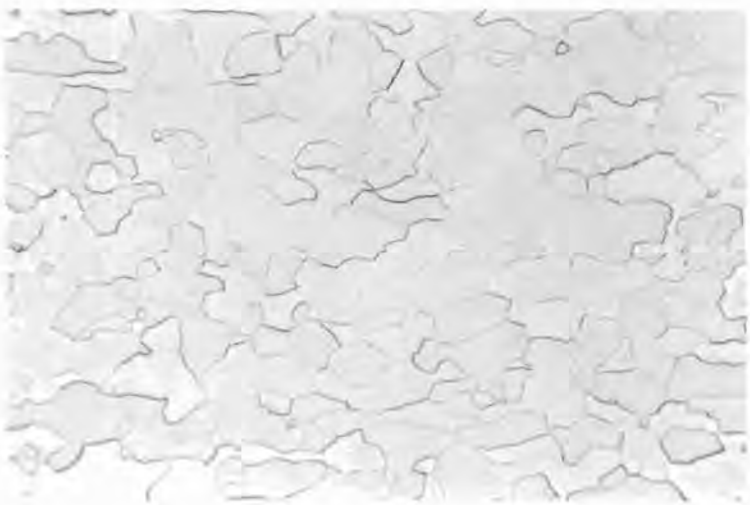


Figure 12

PHOTOMICROGRAPH OF 0.008-INCH MOLYBDENUM-0.5% TITANIUM ALLOY SHEET, "AS RECEIVED" BEFORE WELDING, SHOWING COMPLETE RECRYSTALLIZATION

This material appeared to be free from contamination.

Magnification: 300X

had a measured microhardness of 182-235 DPH in the interior of the sheet and 146-245 on the surface. In view of the brittleness of the recrystallized material, the difficulties in welding are understandable.

Substantially better results were obtained with the Lot 4 material, particularly when welding with a 0.75-inch radius tip. Strengths were higher and more consistent than had been obtained with any previous 0.010-inch gage. It was concluded that the quality of the weldment materials was primarily responsible for this improvement.

2. Metallographic Studies on 0.0055-Inch Material

Specimens of 0.0055-inch molybdenum alloy, produced under the conditions noted for Items 1 and 2 of Table IX, were sectioned and examined metallographically. A number of the specimens fractured during sectioning, as noted below. These fractured specimens obviously contained cracks.

Sheet Gage, inch	Welding Tip Radius, inch	Direction of Sectioning*	Total	Examined	Broken During Sectioning
0.0055	0.25	Longitudinal	25	14	11
		Transverse	25	14	11
0.0055	0.50	Longitudinal	25	5	20
		Transverse	25	4	21

* Relative to direction of tip displacement during welding.

Although the material supplied was designated as "descaled" or "pickled," it appeared that surface contamination of the sheet might be responsible for the gross cracking accompanying welding. Various investigators have agreed that contamination, especially surface contamination, adversely affects the transition temperature and ductility of molybdenum and its alloy in general (21-30), and of weldments in these materials in particular (21-26). Since contamination usually exists as a gradient, being heaviest on the surface and progressively decreasing toward the center, and since hardness is known to increase with the degree of contamination (29), microhardness measurements were made on the 0.005-inch molybdenum alloy. These measurements indicated a hardness of 324 DPH in the center of the sheet and readings of 336 to 366 on the surfaces. Consequently, the contamination theory appeared justified.

The extent of surface contamination can also be detected by recrystallization of the sheet material; according to Universal Cyclops Corporation, heating the molybdenum alloy to a temperature of 2450°F for 10 minutes in a dry hydrogen atmosphere has been deemed a convenient recrystallization technique for this purpose. Therefore, as a further check on the degree of contamination, both welded and unwelded specimens of the 0.0055-inch material were recrystallized by the above technique by the courtesy of Universal Cyclops Corporation.

Subsequent metallographic examination revealed varying degrees of contamination. In some instances it extended through the entire thickness of the 0.0055-inch material, as shown in Figure 13A. Minimum contamination of the specimens examined extended to 0.0028 inch below the surface (Figure 13B).

Photomicrographs of cracked specimens recrystallized after welding are of particular interest (Figures 14-16). The cracks all apparently originated in the contaminated area, and in some instances extended into areas relatively free from contamination. The cracks in Figure 14 occurred in a contaminated zone remote from the weld. Figure 15 shows a crack which started at the heavy contamination at the edge of the weld and progressed upward into the sheet, stopping at an uncontaminated grain, which possibly had sufficient ductility to absorb the local strain. The photomicrograph in Figure 16, which shows a series of microcracks, indicates a considerable degree of plastic flow in spite of contamination. Some of the contaminated surface of the upper foil at A was extruded into the lower foil, suggesting that under certain circumstances with ultrasonic activation, even contaminated material may exhibit some degree of ductility. This extruded material, however, is separated from the lower sheet by microcracks located within the contaminated material.

The effect of this contamination on ultrasonic weldability is illustrated in Figure 17. A heavily contaminated piece shattered during welding, while one with a slightly contaminated surface demonstrated plastic flow and good susceptibility to welding.

The above provides reasonable evidence that surface contamination and recrystallization constituted major barriers to achieving consistently sound, crack-free welds in this molybdenum alloy. When quality material fabricated under carefully controlled and standardized conditions becomes available, it seems clear that ultrasonic welding will become practical.

3. Metallographic Studies on 0.010-Inch Material

The higher and more uniform tensile-shear strengths obtained on the 0.010-inch material of Lot 4 indicated a markedly reduced tendency to crack. Twenty-nine specimens welded with the 0.50-inch-radius welding tip (Item 4 in Table IX) were examined metallographically with the following results.

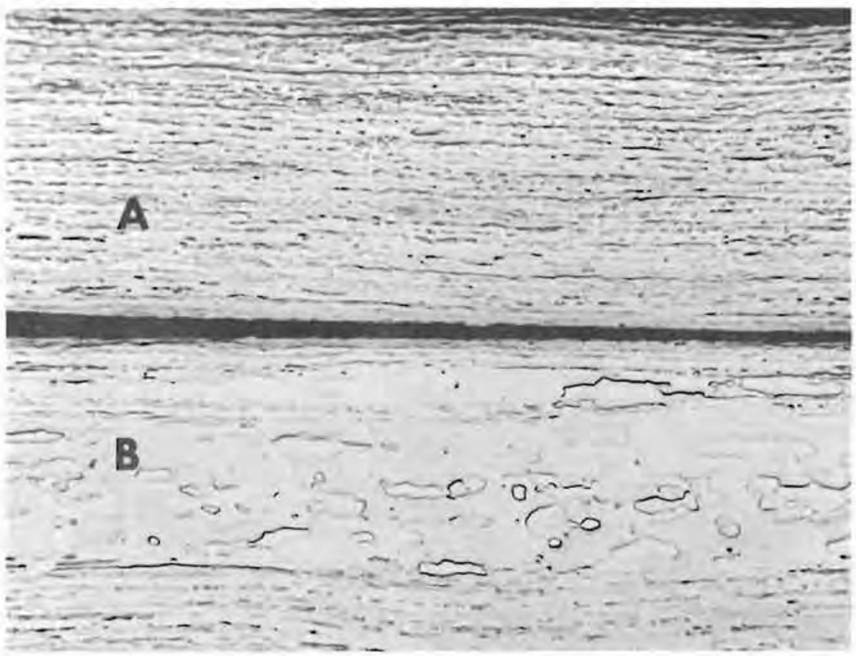


Figure 13

CONTAMINATION OF 0.0055-INCH MOLYBDENUM-0.5% TITANIUM ALLOY SHEET, AS APPARENT AFTER RECRYSTALLIZATION FOR 10 MINUTES AT 2450°F IN DRY HYDROGEN ATMOSPHERE

Depth of Contamination: A. Total
B. 0.028 inch

Magnification: 250X

Figure 14

CRACK IN 0.0055-INCH MOLYBDENUM-0.5% TITANIUM ALLOY SHEET
LOCATED REMOTE FROM WELD AND FOLLOWING CONTAMINATED AREA

Specimen ultrasonically welded and recrystallized.

Magnification: 300X

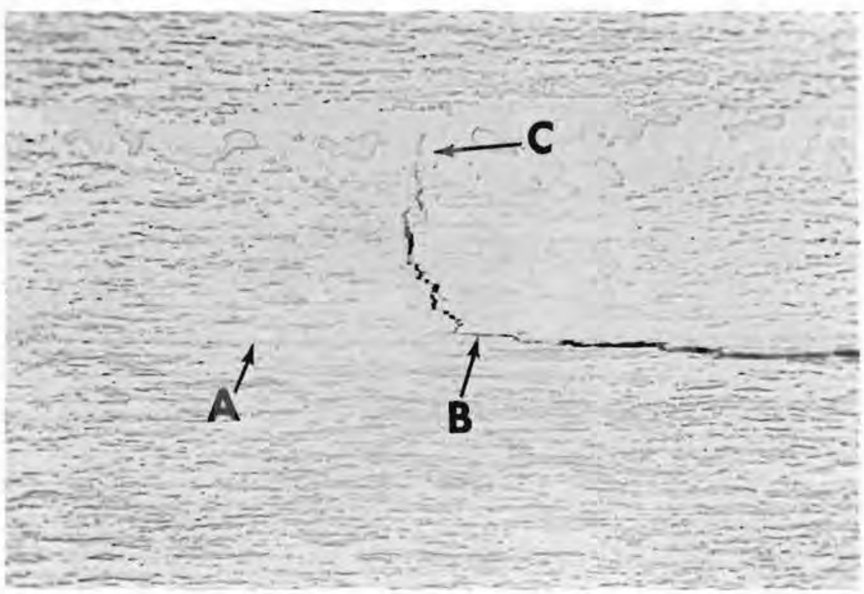


Figure 15

CRACK OBSERVED AT EDGE OF ULTRASONIC WELD (A)
IN CONTAMINATED 0.0055-INCH MOLYBDENUM-0.5% TITANIUM ALLOY

Specimen recrystallized after welding.

Note that crack started at heavily contaminated weld interface (B) and was arrested at an uncontaminated grain (C)

Magnification: 300X

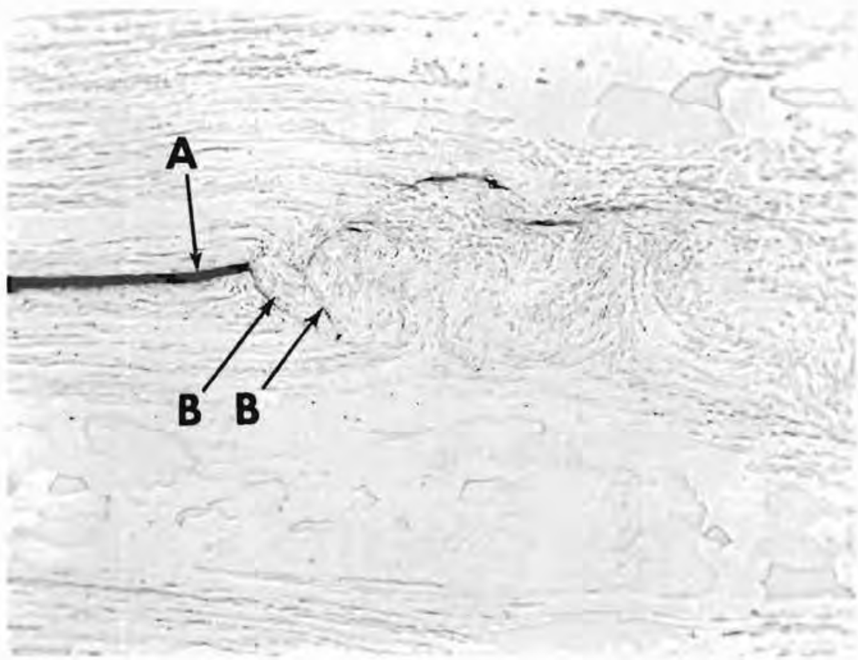
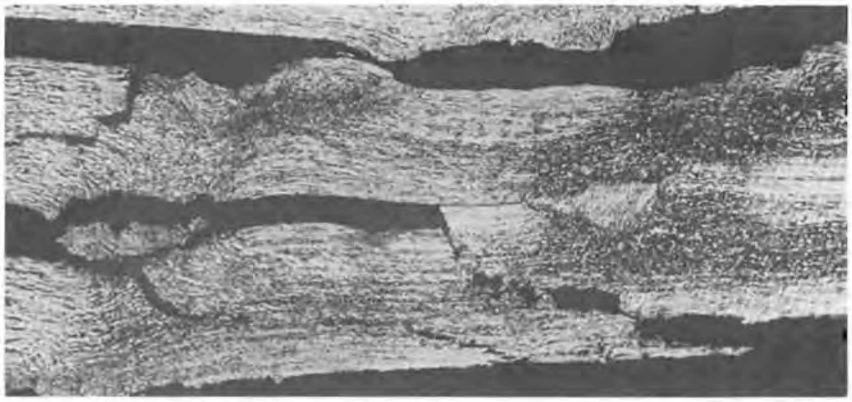


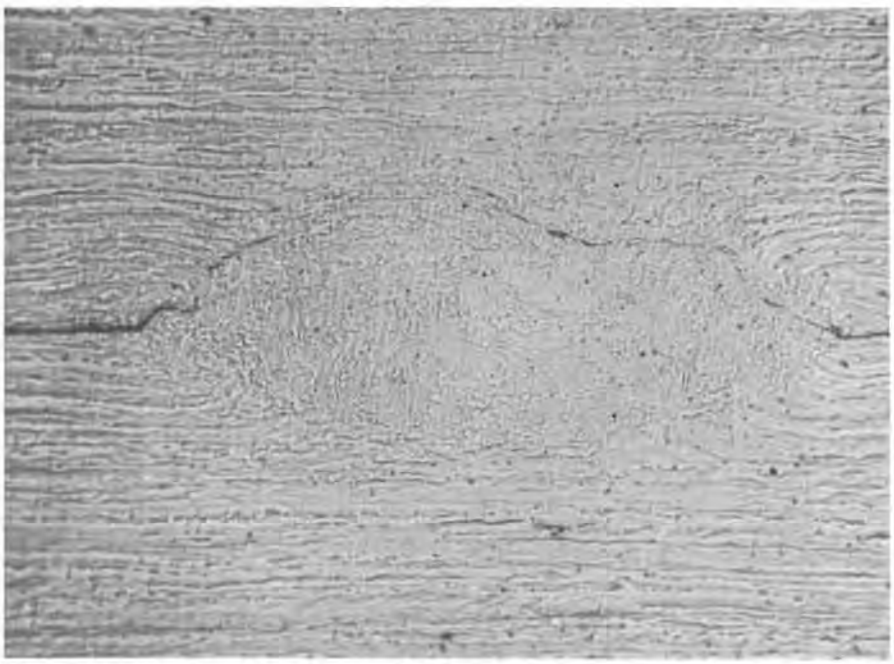
Figure 16

SYSTEM OF MICROCRACKS ASSOCIATED WITH ULTRASONIC WELD
IN CONTAMINATED 0.0055-INCH MOLYBDENUM-0.5% TITANIUM ALLOY

Magnification: 300X



a. 0.0055-Inch, Lot 3, Heavily Contaminated
Magnification: 120X



b. 0.010-Inch, Lot 4, Slightly Contaminated
Magnification: 500X

Figure 17

ULTRASONIC WELDS IN MOLYBDENUM-0.5% TITANIUM ALLOY, SHOWING EFFECT OF CONTAMINATION

Direction of Sectioning*	No. of Specimens	Metallurgical Results Good Bond, No Crack	Good Bond, One Crack	Good Partial Bond	No Bond
Longitudinal	14	1	2	3	8
Transverse	15	2	4	4	9

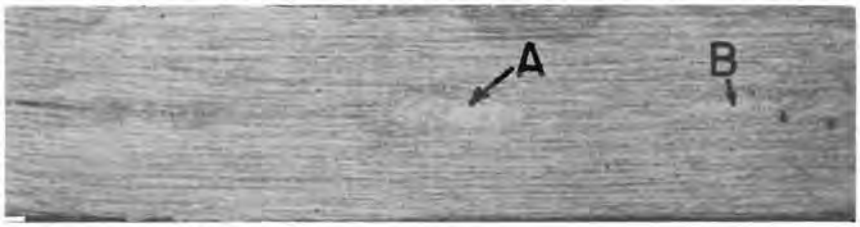
*Relative to the direction of tip displacement during welding.

Figure 18 is an example of a "good partial bond" with local plastic flow and interpenetration at locales A and B, and with no evidence of cracking. This mutual interpenetration, which extends to as much as 25 percent of the sheet thickness, reveals a high degree of ductility.

Cracking in the 0.010-inch material was far less pronounced than in the 0.0055-inch gage. The cracks which did result were generally microcracks, rather than gross cracks, and were usually concentrated on the weld interface. None of the cracks in the 0.010-inch material extended to the surface of the sheet, an observation which was confirmed by planar sectioning and by inspection of random specimens with SUPER PENETREX (as described in Section IV).

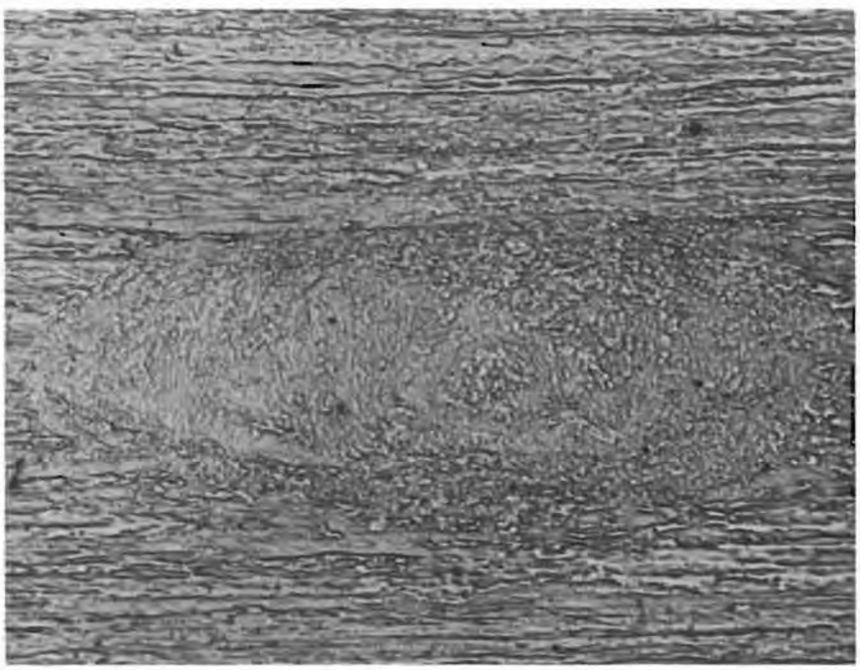
Specimens of welded and unwelded 0.010-inch material were also recrystallized by Universal Cyclops Corporation for 10 minutes at 2450°F in dry hydrogen atmosphere, in the same manner as the 0.0055-inch material. Microhardness measurements before recrystallization indicated a DPH of 330 at the center of the sheet and 297-314 on the surfaces; hence, surface contamination appeared less likely. Examination of the recrystallized material indicated that contamination was generally confined to a layer from 0.0009- to 0.0011-inch deep on the surface, with occasional traces within the sheet. In Figure 19 it is noted that a series of microcracks was located in a contaminated area within the sheet above the weld interface.

Thus the cracking in molybdenum-0.5% titanium alloy appears directly related to the contamination of the sheet material. With the improved manufacturing techniques currently being developed under the Department of Defense Refractory Metals Sheet-Rolling Program, the purity of the material should be improved, and the ultrasonic weldability of the material should be expected to improve considerably.



a. Cross Section Showing Excellent Bond With Heavy Local Interpenetration (A and B)

Magnification: 50X



b. Detail A from Cross Section

Magnification: 300X

Figure 18

PHOTOMICROGRAPHS OF ULTRASONIC WELD
IN 0.010-INCH MOLYBDENUM-0.5% TITANIUM ALLOY (LOT 4)

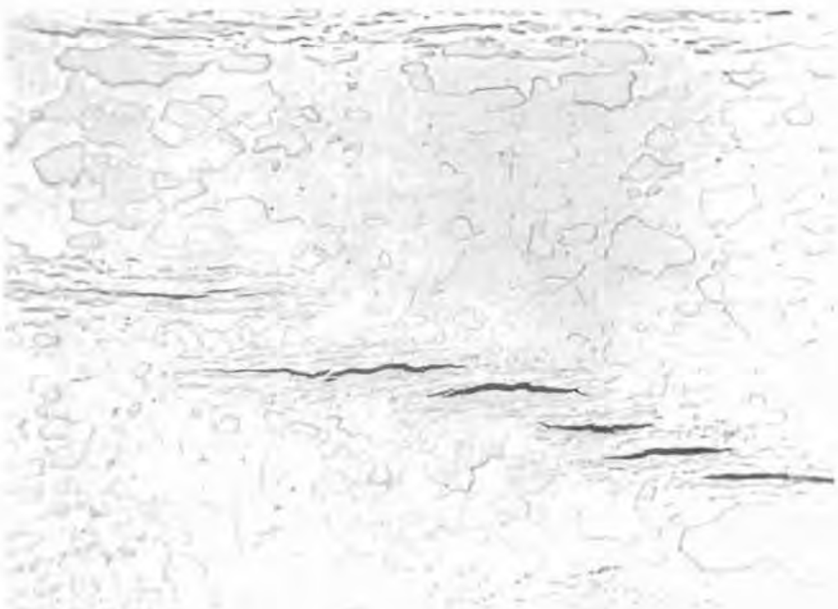


Figure 19

PHOTOMICROGRAPH SHOWING SURFACE CONTAMINATION
AND MICROCRACKS IN CONTAMINATED AREA WITHIN THE SHEET
IN 0.010-INCH MOLYBDENUM-0.5% TITANIUM ALLOY

Depth of Surface Contamination: 0.0009 to 0.0011 inch

Specimen recrystallized after welding.

Magnification: 300X

VI. WELDING OF NIOBIUM-10% TITANIUM-10% MOLYBDENUM (D-31) ALLOY

During initial studies with the niobium-10% titanium-10% molybdenum alloy, this material presented difficulties. Evidence of bonding was obtained, but weld strengths were low and erratic, and there was little evidence of the interfacial metal flow that had been obtained with the molybdenum-0.5% titanium alloy. Later experiments with different lots of material showed markedly improved weldability, and significant strengths were obtained in gages up to 0.015 inch.

A. WELDING EXPERIMENTS WITH LOTS 1 AND 2 MATERIAL

On the basis of the welding energy-hardness-thickness equation (page 15), calculations indicated the minimum electrical energy required for welding this niobium alloy to be as follows:

Gage, inch	Energy, watt-seconds
0.005	460
0.008	870
0.010	1100
0.015	2200
0.020	3200

Initial attempts to weld the 0.005-inch and the 0.008-inch material were generally unsuccessful over a range of welding machine settings: powers ranging from 800 to 3000 watts, clamping forces from 100 to 900 pounds, and weld times from 0.3 to 1.5 seconds. Throughout these ranges, when welds were produced at all, they exhibited only moderate tensile-shear strength. A degree of success was achieved with 0.008-inch sheet with machine settings of 3000 watts power, 700 pounds clamping force, and 1.0 second weld time, and with the clamping force maintained for 2 seconds after the conclusion of the ultrasonic power. Several specimens of this gage were also welded under these same conditions with an interleaf of 0.0005-inch pure nickel foil. Tensile-shear tests on one specimen of each type resulted in a strength of 43 pounds for the non-interleaf weld and 84 pounds for the interleaf weld.

Figure 20 is a typical photomicrograph of a portion of one of the non-interleaf welds. Some areas of this section appear to be in intimate contact; surface film was apparently broken only locally and was not displaced.

In an effort to explain these observations, and to isolate welding conditions productive of effective bonds, supplementary studies were conducted as described below.

1. Measurement of Temperature Rise in the Weld Zone

To approximate the proper clamping force, the temperature rise in the weld zone was measured as previously described.

Satisfactory data could not be obtained with the thinner gage materials; however, the 0.020-inch sheet permitted this type of measurement. Temperature data were obtained using a power level of 1500 watts and a weld time of 0.6 second; this is admittedly below the minimum required for welding the 0.020-inch gage, but nevertheless should be adequate for indicating the best clamping force. The results, plotted in Figure 21, show a maximum temperature at approximately 600 pounds clamping force.

2. SWR Ellipse Area Data

The standing-wave-ratio technique was used to confirm the optimum clamping force for the thinner sheets. Results of typical measurements, plotted in Figure 22, show an optimum clamping force of approximately 400 pounds for the 0.005-inch gage, and 700-800 pounds for the 0.015-inch sheet.

3. Tip Displacement Curves

Further welding with the 0.005-inch material indicated that bonds of some strength could be obtained at machine settings of 750 watts, 300 pounds, and 0.5 second. The average tensile-shear strength of five specimens welded under these conditions was 41 pounds, with a standard deviation of approximately 5 pounds. Metallographic examination of the specimens indicated that the bonds had essentially the same metallurgical characteristics as obtained in the earlier experiments (Figure 20).

As the above welds were produced, tip displacement data were recorded. All five specimens produced curves having the configuration of Figure 23. This is comparable to the curve of Figure 8B for molybdenum-0.5% titanium alloy, which represented a weld of below-average strength for that material.

4. Effect of Pre-Weld Surface Treatment

Etch-cleaning the sheets prior to welding was studied. One group of specimens was degreased in a detergent solution, as was done with earlier specimens of this material, and a second group was etched with 10 parts hydrofluoric acid, 30 parts nitric acid, and 50 parts lactic acid. All specimens were welded at the same machine settings.

Figure 20

PHOTOMICROGRAPH OF ULTRASONIC WELD
IN 0.005-INCH NIOBIUM-10% MOLYBDENUM-10% TITANIUM (D-31) ALLOY
DEGREASED BEFORE WELDING

Magnification: 500X

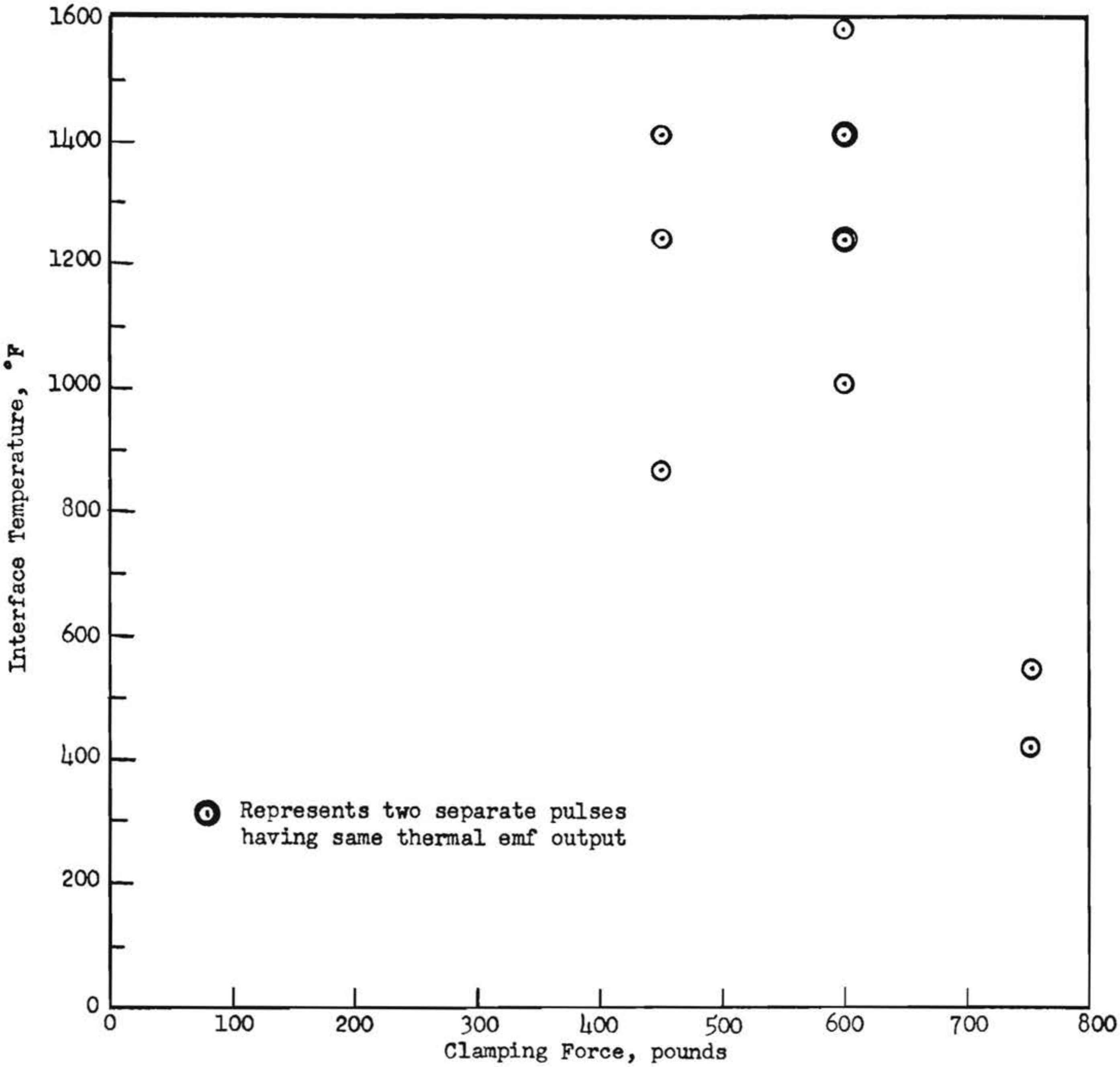


Figure 21

TEMPERATURE RISE IN WELD ZONE AS FUNCTION OF CLAMPING FORCE DURING WELDING OF 0.020-INCH D-31 ALLOY

Input Power: 1500 watts
Weld Time: 0.6 second

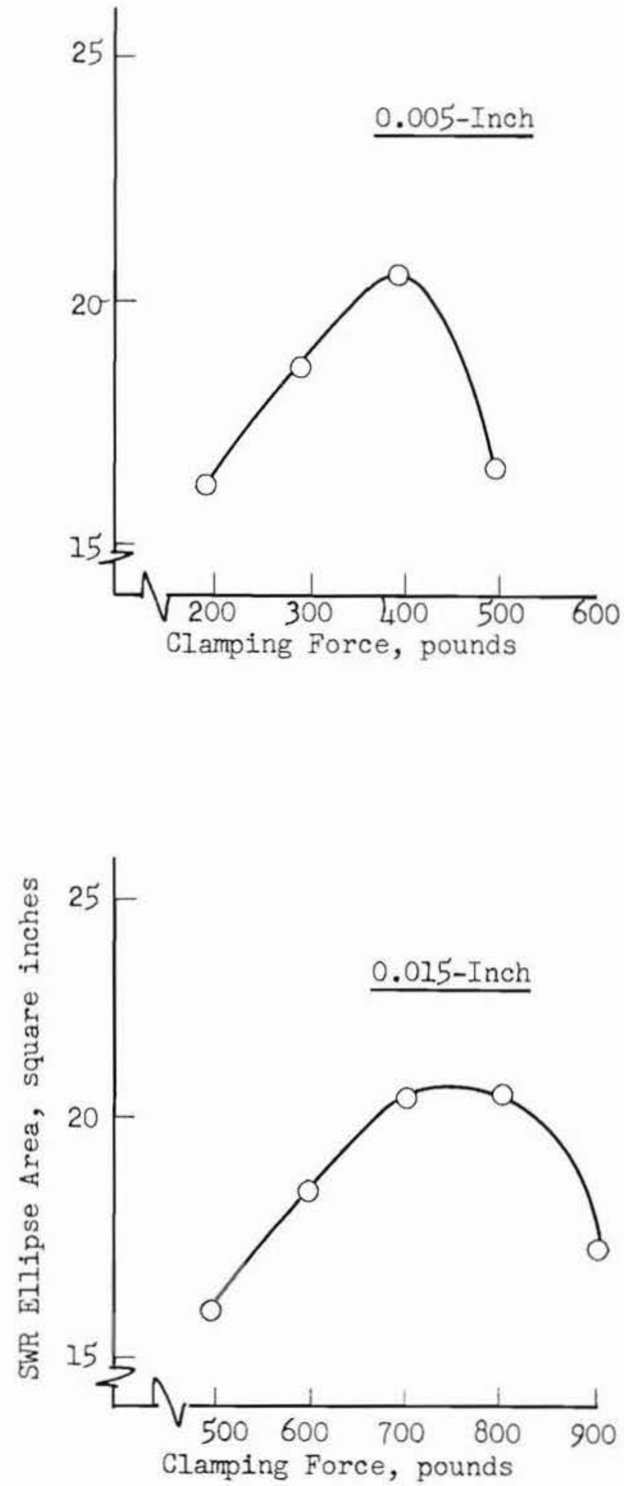


Figure 22

CURVES OF SWR ELLIPSE AREA VS. CLAMPING FORCE
FOR TWO GAGES OF D-31 ALLOY

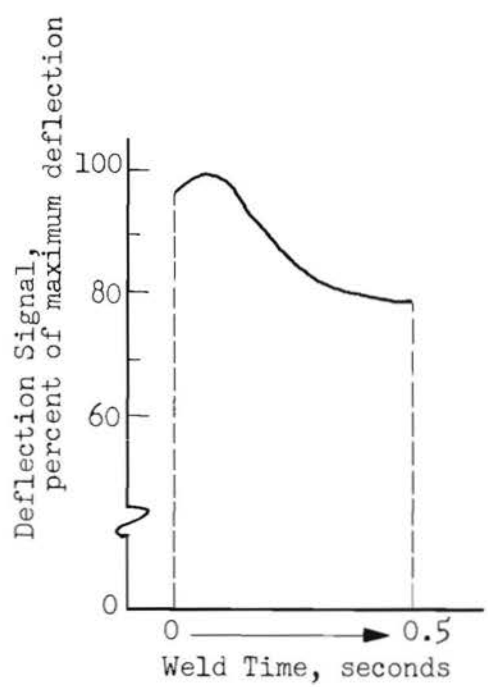


Figure 23

WELDING TIP DEFLECTION SIGNAL RECORDING
FOR 0.005-INCH D-31 ALLOY

The degreased specimens showed interfacial microstructure similar to that in Figure 20. Bonding occurred in discontinuous regions along the interface, and the isolated void areas were apparently due to irregularities on the parent metal. Such discontinuities in the bond zone were generally absent in the etched specimens (Figure 24 is representative). Apparently the etching removed surface films and some irregularities to permit improved metallurgical continuity over more extensive regions of the bond area.

B. WELDING OF LOTS 3 AND 4 NIOBIUM ALLOY

The D-31 alloy sheet identified as Lots 3 and 4 showed improved weldability over that of Lots 1 and 2. Strengths were higher and more uniform, and metallographic examination revealed good bonding. Whereas previous welds had been made with a sonotrode tip having a 3-inch spherical radius and a flat anvil face, this work involved tip radii in the range of 50 to 100 times the sheet thickness (and a flat anvil face), since this change had effected improvement in welding other materials, including molybdenum-0.5% titanium alloy. Welding machine settings for the three gages were varied within the range of 750 to 3200 watts power, 300 to 1100 pounds clamping force, and 0.5 to 0.75 second weld time. The weld quality in materials from different lots and different sheets within the same lot was considered. The welds were tested in tensile-shear, and representative specimens were evaluated metallurgically.

1. Weld Strength Data

The welding conditions and tensile-shear strength data for 17 groups of weldments are presented in Table X. Examination of these results yields interesting aspects on the weldability of this niobium alloy.

Ten series of tests were made with 0.005-inch material, 5 each of Lots 3 and 4, duplicate sets being welded under identical conditions. In every instance, the Lot 4 material showed substantially higher weld strength averages, and variability was considerably reduced. The average strength for all the Lot 3 specimens was 58 pounds, while that for the Lot 4 specimens was 79 pounds; the standard deviation was significantly greater for Lot 3 than for Lot 4. Material quality thus apparently appeared to have an influence on weld quality, strength, and consistency.

The best results for both 0.005-inch material lots were obtained with the welding tip radius of 0.75 inch, at machine settings of 1600 watts power, 700 pounds clamping force, and 0.75 second weld time (Series 9 and 10). The welding energy amounted to 1200 watt-seconds, which is substantially higher than the 420 watt-seconds minimum predicted from the energy-hardness-thickness equation. The data in Table X suggest a significant effect of welding tip radius on strength and variability. For both lots of material, average weld strength increased as the tip radius was increased from 0.25 to 0.75 inch, and variability was substantially less with the larger tip radii.

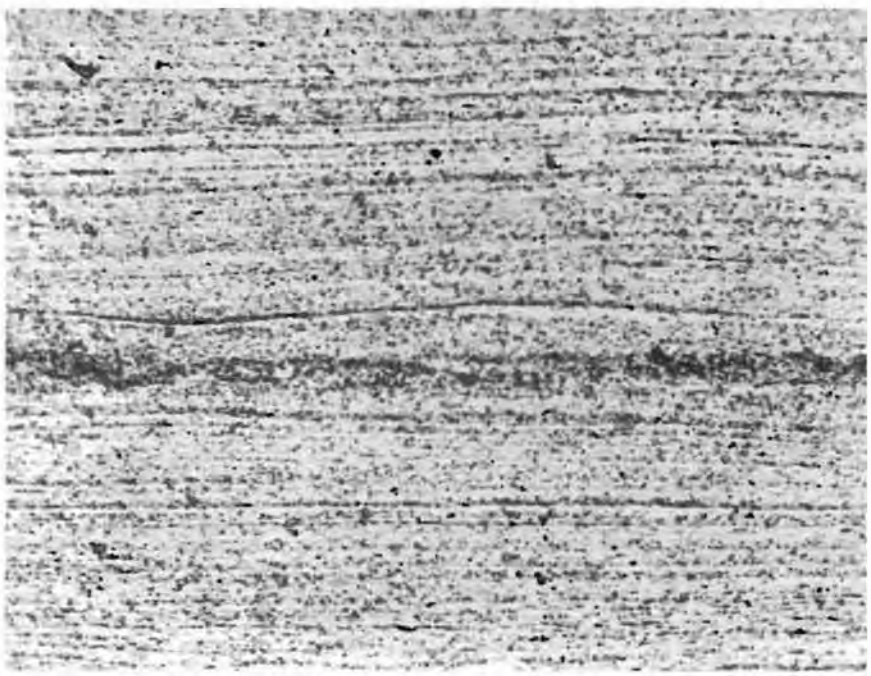


Figure 24

PHOTOMICROGRAPH OF ULTRASONIC WELD
IN 0.005-INCH D-31 ALLOY (LOT 2)

Surfaces etched with acid mixture
(10 parts HF, 30 parts HNO_3, and 50 parts lactic acid)
before welding

Magnification: 500X

Table X

TENSILE-SHEAR STRENGTH DATA FOR ULTRASONIC WELDS
IN NIOBIUM-10% TITANIUM-10% MOLYBDENUM ALLOY (D-31 ALLOY)

				Welding Machine Settings				Tensile-Shear Strength			
Series No.	Sheet Gage, inch	Material Lot No.	Welding Tip Radius, inch	Power, watts	Clamping Force, pounds	Weld Time, second	No. of Specimens	Average, pounds	Standard Deviation pounds	Expected Minimum, pounds	Notes
1	0.005	3	0.25	850	400	0.75	30	55	16	7	
2	0.005	4	0.25	850	400	0.75	10	70	14	28	
3	0.005	3	0.50	1400	650	0.75	11	48	25	27	
4	0.005	4	0.50	1400	650	0.75	11	63	17	12	Figure 25
5	0.005	3	0.50	1400	700	0.75	13	63	12	27	
6	0.005	4	0.50	1400	700	0.75	10	79	9	52	
7	0.005	3	0.75	750	300	0.5	20	50	19	-7	Figures 27, 28
8	0.005	4	0.75	750	300	0.5	10	64	21	1	
9	0.005	3	0.75	1600	700	0.75	21	72	20	12	
10	0.005	4	0.75	1600	700	0.75	14	107	14	65	Figure 26
11	0.010	3	1.0	2000	750	0.75	13	273	23	204	Surface degreased
12	0.010	3	1.0	2000	750	0.75	6	135	78	-99	Surface abraded
13	0.010	3	1.0	3200	1000	0.75	10	132	25	57	Tabs cut from
14	0.010	3	1.0	3200	1000	0.75	10	119	16	71	different sheets
15	0.010	3	1.0	3200	1000	0.75	20	129	43	0	in same lot
16	0.015	3	1.0	2800	800	0.75	16	245	47	104	
17	0.015	3	1.0	3200	1100	0.75	20	190	53	31	

In addition, comparison of Series 3 and 4 with Series 5 and 6 suggests that the material may be somewhat sensitive to clamping force. With only 50 pounds increase in clamping force (650 to 700 pounds), and with all other conditions remaining constant, a 25 to 30 percent increase in strength was obtained and standard deviation was markedly reduced.

Best results with the 0.010-inch material (Series 11) were obtained with a welding tip radius of 1.0 inch, at welding conditions of 2000 watts power, 750 pounds clamping force, and 0.75 second weld time with material that had previously been merely degreased. These welds had an average strength of 273 pounds, with a standard deviation of 23 pounds. Abrasion of the surface prior to welding reduced weld strength by about one-half, and the strengths showed wide variability. Increases in welding power and clamping force also resulted in lower strength welds. The varied response of the material used on the program to ultrasonic welding is exemplified by the results in Series 13, 14, and 15, which represent welds produced under identical conditions from three different sheets in the same material lot.

Significant weld strength was also obtained in the 0.015-inch material (Series 16 and 17), but inasmuch as maximum average strength (245 pounds) was below the maximum average obtained with the 0.010-inch sheet (273 pounds), it appears that some further effort is required to establish the most effective welding conditions for this gage.

2. Metallurgical Evaluation

Selected specimens of 0.005-inch weldments from Series 1-10 in Table XI were sectioned, mounted, and examined metallographically. Typical examples are shown in Figures 25 to 28, which are referenced with the appropriate series on the table.

Most of the welds in the Lot 4 material which were examined were characterized by good bond continuity over the entire weld interface and lack of surface film residues in the interfacial zones, as shown in Figures 25 and 26.

Several specimens from Series 7 (Lot 3), in which the specimens were welded at a clamping force below the value indicated by the threshold studies, were examined metallographically, with the results shown in Table XI. Of these nine welds, three were considered to have satisfactory bonds with no cracks, and five showed poor bonding or no bond at all. It is interesting to note that only one specimen of this group contained microcracks, and none of the weldments in the D-31 alloy examined exhibited the gross cracking that had been characteristic of welds in the molybdenum-0.5% titanium alloy. A photomicrograph of the best of the welds in Table XI (Figure 27) showed bond quality equivalent to that obtained with Lot 4 material.

Table XI

SUMMARY OF METALLURGICAL STUDIES OF ULTRASONICALLY SPOTWELDED 0.005 INCH D-31 ALLOY WITH THE CLAMPING FORCE BELOW THAT INDICATED BY THE THRESHOLD STUDIES

(See Study No. 7, Table X)

Specimen No.	Bond Quality	Cracking	Figure No.
2	Good	None	27
4	Satisfactory	None	
6	Poor	None	
8	Very Poor	None	
10	Good	None	
12	Satisfactory	Edge micro-cracks	28
14	No weld	None	
16	No weld	None	
18	No weld	None	

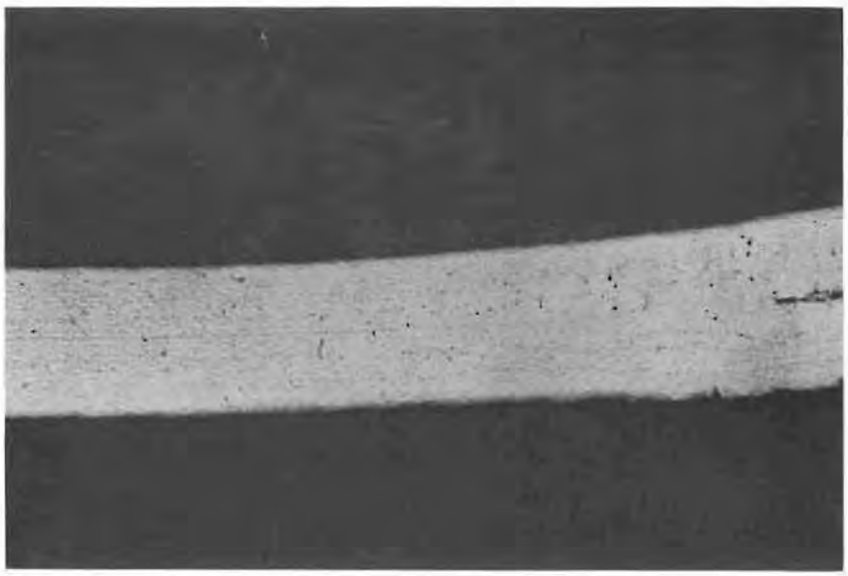
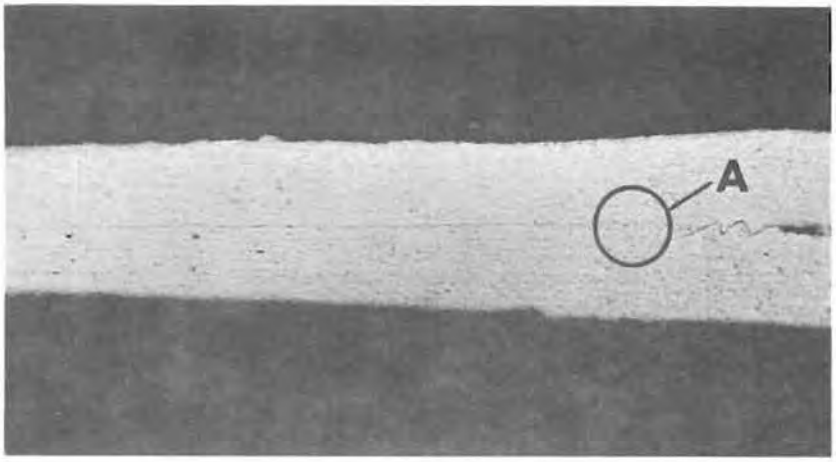


Figure 25

PHOTOMICROGRAPH OF ULTRASONIC WELD
IN 0.005-INCH D-31 ALLOY (LOT 4)
(Series 4 in Table X)
Magnification: 400X

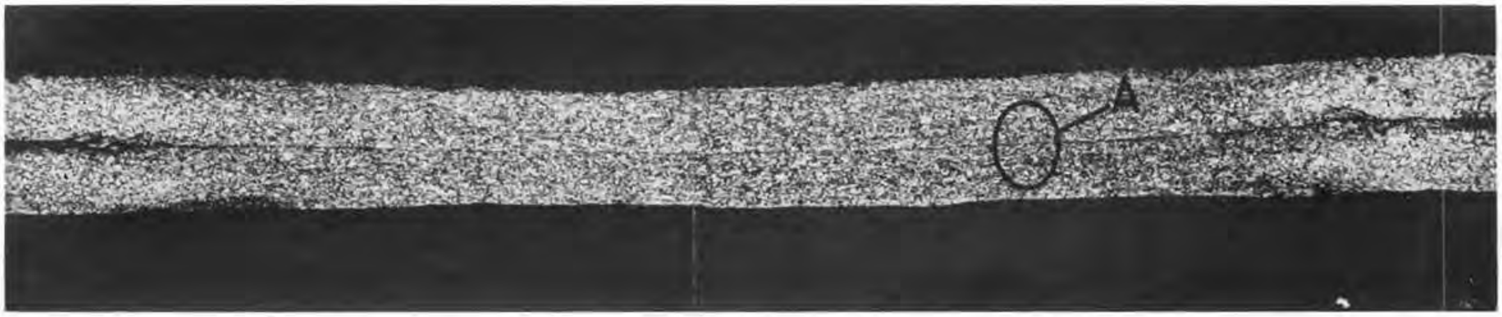


a. Cross Section of Weld With indication of Edge Microcrack
Magnification: 100X

b. Detail A from a Above
Magnification: 500X

Figure 26

PHOTOMICROGRAPH OF ULTRASONIC WELD IN 0.005-INCH D-31 ALLOY (LOT 4)
(Series 10 in Table X)



a. Cross Section of Weld
Magnification: 100X

b. Detail A of Section a Above, Showing Intimacy of Bond

Magnification: 500X

Figure 27

PHOTOMICROGRAPH OF ULTRASONIC WELD
IN 0.005-INCH D-31 ALLOY (LOT 3)
MADE WITH LOW CLAMPING FORCE

(Series 7 in Table X)

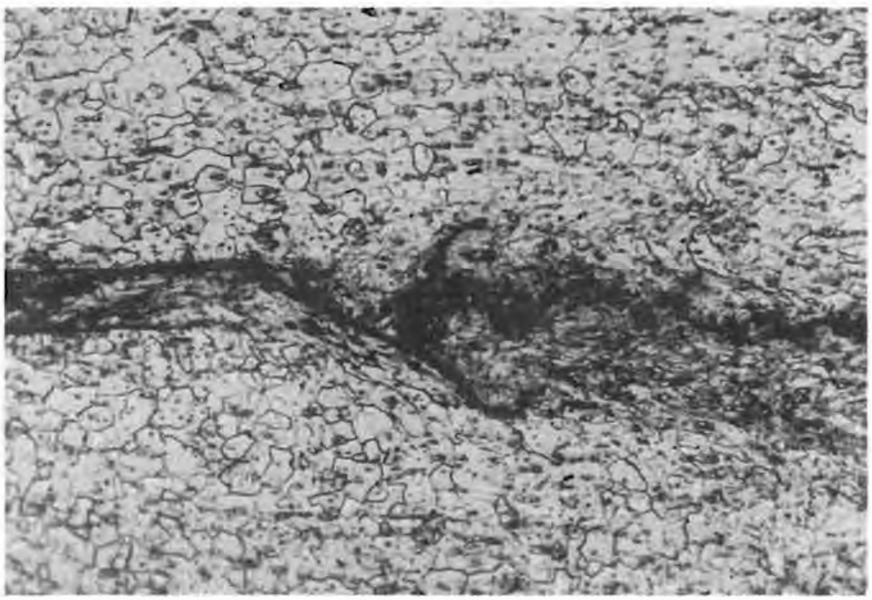


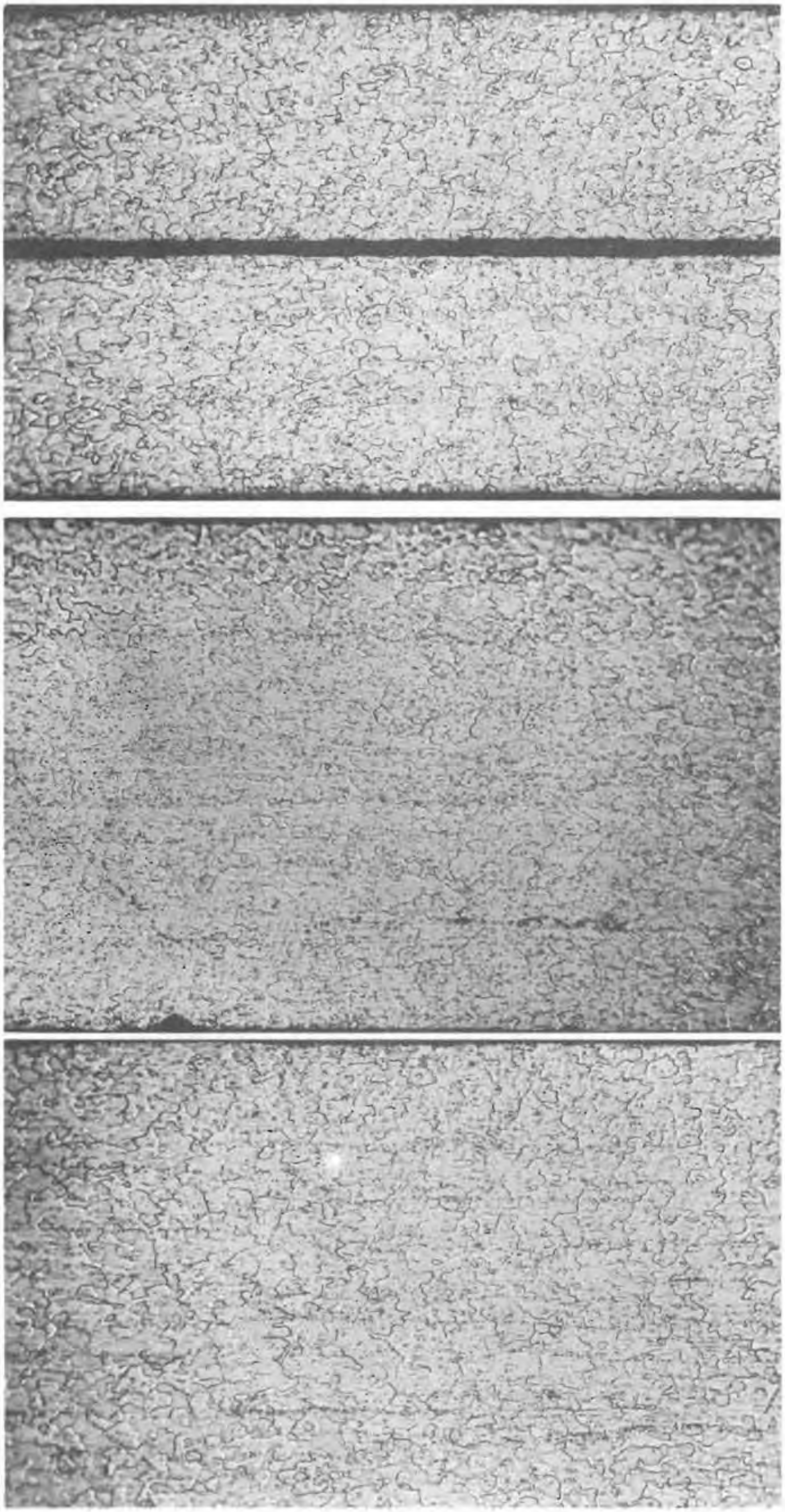
Figure 28

PHOTOMICROGRAPH OF ULTRASONIC WELD
IN 0.005-INCH D-31 ALLOY (LOT 3)
MADE WITH LOW CLAMPING FORCE, SHOWING EDGE MICROCRACKS
(Series 7 in Table X)
Magnification: 500X

In further effort to determine the cause of the inferior weldability of Lot 3, additional studies were made on the unwelded material. As previously noted, this niobium alloy possesses its best properties when cold-worked and stress-relieved. With recrystallization, some of the ductility is lost, and the ductile-brittle transition temperature increases. For this reason, the material had been ordered in the stress-relieved condition. However, photomicrographs of the various gages in Lots 3 and 4 (Figure 29) showed the structure in each case to be partially recrystallized; this phenomenon with nominally stress-relieved material has been noted in other publications (34), although producer's data (7, 8) show material without any traces of recrystallization. The microstructures of all four specimens were essentially identical, and no difference whatever between the 0.005-inch material of Lots 3 and 4 could be detected (Figure 29).

It was then considered that the difference in weldability may be due to surface contamination which is not discernible by normal metallographic methods. It has been noted (29) that there is an appreciable increase in surface hardness of this niobium alloy after exposure to an argon atmosphere contaminated with oxygen. Also Evans (35) from the Defense Metals Information Center advised the use of traverse microhardness tests to check for contamination. Microhardness studies were therefore made on each of the four materials In Lots 3 and 4. The results, presented in Table XII, show no significant difference. All hardness measurements in the core of the material and on both surfaces fall within the same range.

No explanation has therefore been found for the difference in weldability between the Lots 3 and 4 materials.



A. 0.005-Inch, Lot 3

B. 0.005-Inch, Lot 4

C. 0.010-Inch, Lot 3

D. 0.015-Inch, Lot 3

Figure 29

MICROSTRUCTURES OF THREE GAGES OF D-31 ALLOY
Magnification: 300X

Table XII

MICROHARDNESS STUDIES OF D-31 ALLOY FOIL AND SHEET USED FOR TENSILE-SHEAR STUDIES IN TABLE X

50 grams load, Accuracy ± 4%

			Microhardness, DPH					
			Surface I		Center		Surface II	
Gage, inch	Material	Series No.	Readings	Average	Readings	Average	Readings	Average
0.005	Lot 3	1,3,5,7,9	207,207,195	203	200,200,200	200	200,195,200	198
0.005	Lot 4	2,4,6,8,10	210,210,195	205	210,207,195	204	200,200,207	202
0.010	Lot 3	11,12,13,14,15	207,200,195	201	214,195,207	202	210,210,195	205
0.015	Lot 3	16,17	210,200,195	202	200,200,210	203	195,214,195	201

VII. WELDING OF TUNGSTEN

The pure tungsten sheet material proved to be more difficult to weld than either the molybdenum-titanium or the niobium-titanium-molybdenum alloys. As noted in Section II (Table IV), the Lots 1 and 2 material were received in the as-rolled condition; they demonstrated negligible room temperature ductility, and delaminated under bending stresses. Measured hardness values ranged from 376 to 458 DPH. On the basis of these hardness measurements, the estimated welding energy requirements were calculated to be 850 watt-seconds for the 0.005-inch sheet and 3000 watt-seconds for the 0.010-inch material.

A. WELDING EXPERIMENTS WITH A SINGLE POWER PULSE

Initial attempts to weld the 0.005-inch tungsten were oriented to determine suitable welding machine settings to achieve good bonds. Power was varied from 1600 to 3000 watts, clamping force from 300 to 900 pounds, and weld time from 0.1 to 0.6 second. Various problems were encountered: adhesion of the weldment to the tip and the anvil, often accompanied by delamination of the sheet; weld cracking; marked oxidation of the metal; and incomplete bonding or negligible bonding.

Further efforts were made to establish the optimum clamping force for this thin gage. Welds were made at 1600 watts power, 0.3 second weld time, and at clamping forces ranging from 300 to 900 pounds. The manual peel method of weld evaluation, which is effective with the more ductile materials, could not be used with tungsten because of its brittleness. Measurements of maximum temperature rise were impractical with such thin material, and standing-wave-ratio measurements were difficult, also probably because of the thin material. Tensile-shear tests showed weld strengths varying from 15 to 38 pounds, and indicated the most effective clamping force to be in the range of 500-700 pounds.

Welding was attempted using interleaves of 0.0005-inch foils of zirconium, nickel, titanium, and molybdenum. Best results in this group were obtained with a molybdenum interleaf which produced a single weld with 37 pounds tensile-shear strength.

Efforts to weld the 0.010-inch tungsten produced bonds of low and erratic strength, with weld cracking, tip sticking, and delamination.

It was apparent that a single weld power pulse could not produce good welds in the thin gages of tungsten, at least in the as-rolled material of Lots 1 and 2.

B. WELDING WITH CRUDE POWER PROGRAMMING

Meanwhile, in the course of other work, the weldability of beryllium had been enhanced with the use of power programming, in which an initial weld pulse at low power is applied for a brief interval, followed by an abrupt increase to high power. The initial pulse seemingly serves to "couple" the sonotrode to the work with relatively low stress and to preheat the material prior to the introduction of full power to effect bonding. This technique, investigated briefly with tungsten, effected a marked improvement in weld strength, and a decrease in strength variability.

Table XIII summarizes the crude power-programmed experiments conducted with 0.005- and 0.010-inch tungsten. It will be noted that the shear strength of welds in the 0.005-inch gage produced with power programming averaged 49 pounds, whereas the average strength with a single power pulse was 23 pounds; also the variability decreased from 82 to 29 percent. This technique therefore appeared to provide an avenue for improvement in the quality of ultrasonic welds in tungsten and other refractory materials.

The data of Table XIII show a limited number of investigations carried out with the 0.010-inch material of Lots 1 and 2. Additional data obtained in welding 0.010-inch tungsten sheet under a concurrent program (31) are included. The material used on this concurrent program, designated as Lot 3, apparently was in the stress-relieved condition and demonstrated greater ductility than Lots 1 or 2. The welds in this material produced under programmed power conditions at the 550-pound clamping force level showed strengths ranging from 52 to 108 pounds, which represent a rather wide variability but substantially higher strengths than any obtained with the as-rolled (Lots 1 and 2) material.

The weldments obtained with the stress-relieved material (Lot 3) as represented in Figure 30 indicate that sufficient plasticity has been obtained to effect a void-free, crack-free weld in the central region of the weld envelope. This apparently can be attributed to the preheating of the sheet with the first pulse of programmed power cycle.

Available time did not permit further exploration of the welding of tungsten sheet, inasmuch as efforts were concentrated on the other two alloys. However, it is believed that further development of power programming, perhaps with the addition of clamping force programming, and the use of stress-relieved material, should permit effective welding of tungsten.

Table XIII

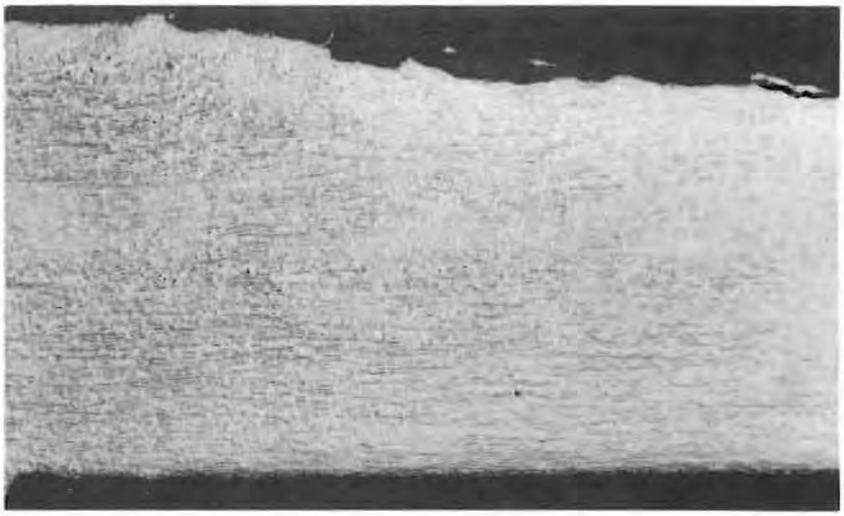
EFFECT OF POWER PROGRAMMING

ON STRENGTH OF ULTRASONIC WELDS IN TUNGSTEN

Material Lot No.	Sheet Gage, inch	Clamping Force, pounds	Power Programming watts/seconds		No. of Specimens	Tensile-Shear Strength	
			First Pulse	Second Pulse		Average, pounds	Standard Deviation, pounds
1	0.005	500	1600/0.3[a]	-	5	23	19
		500	500/0.7	1600/0.3	5	49	14
1	0.010	500	1200/0.7	3600/1.0	5	55	20
		500	1200/0.7	3600/0.5	1	71	-
2	0.010	500	1200/0.7	3600/0.5	1	22	-
3[b]	0.010	500	1200/0.7	3600/0.3	8	46	18
		550	1200/0.7	3600/0.3	6	72	22

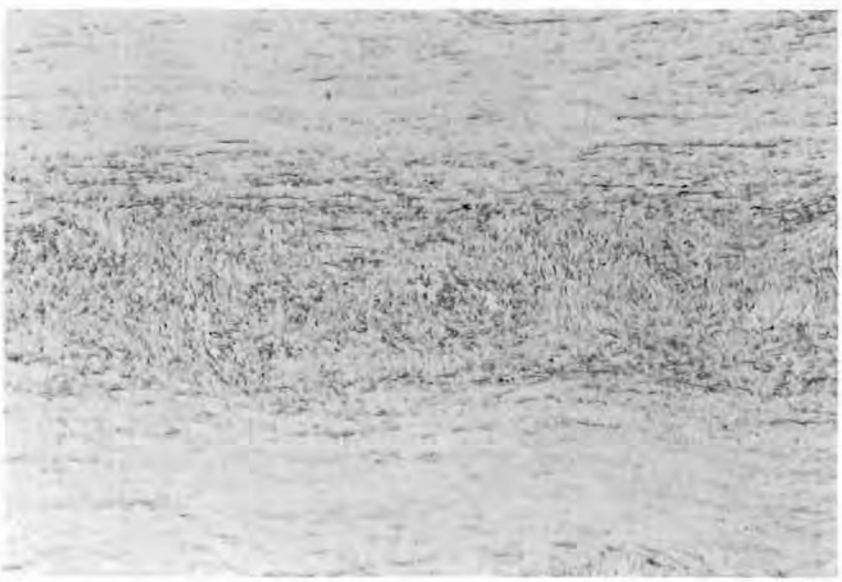
(a) Welded with single power pulse

(b) Data from Ref. 31.



a. Cross Section of Weld Showing Intimate Bonding

Magnification: 90X



b. Section of Above, Showing Mutual Interpenetration of Faying Surfaces and Elimination of Original Interface

Magnification: 200X

Figure 30

PHOTOMICROGRAPH OF ULTRASONIC WELD IN 0.010-INCH TUNGSTEN

VIII. APPROACHES TO IMPROVING WELD QUALITY

It has been shown that the physical properties of the refractory metals and alloys vary widely from lot to lot of any given metal. Since the welding machine settings are dependent upon the physical properties of the materials being joined, frequent adjustments and changes in welding parameters are necessary and this is not conducive to production-type applications of ultrasonic welding. Several approaches which are available for reducing the criticality of welding machine selection as related to changes in material physical properties are outlined here. Brief investigations outside the scope of this program, such as those conducted with tungsten (see Section VII, B), have already demonstrated improved weld quality.

A. APPLICATION OF EXTERNAL HEAT

During ultrasonic welding, a weld-zone temperature rise occurs to about 35-50 percent of the absolute melting point. For materials in which the brittle-ductile transition temperature lies above this range, heat applied immediately before welding usually increases the ductility of the material. This technique has been effective in facilitating the welding of such materials as zirconium.

B. INTERLEAF WELDING

By inserting a thin foil interleaf, usually of a dissimilar metal, in the weld zone between the components being joined, the bonds of refractory metals and alloys frequently will be strengthened, the strength variability of the bonds reduced, and cracking of the parent materials will be reduced. In certain cases, the use of niobium, molybdenum, and tantalum interleaves have proved effective, but the effects on strength are limited to room temperature applications. At high temperatures, the strength of the bond might be no greater than the strength of the interleaf. If the initial metal or alloy has a substantially higher temperature than the interleaf material, this advantage would be cancelled.

C. POWER-FORCE PROGRAMMING

The stepwise variation in the power and clamping force applied during the welding cycle, known as power-force programming, has improved the weldability of materials, the properties of which are not uniform. In power-force programming, an initial weld pulse is applied at low power for a brief interval, followed by an abrupt increase to high power. The initial pulse preheats and/or plasticizes the metal before the stresses of instantaneous full power and force are introduced. When this technique was used with beryllium, weld strength improved while strength variability decreased.

IX. CONCLUSIONS

[and with the D-31 alloy]

Mo, Cb, W

1. Thin gages of molybdenum-0.5% titanium, niobium-10% titanium-10% molybdenum (D-31) alloy, and tungsten were shown to have excellent susceptibility to joining by ultrasonic welding.

2. Cracking tendencies associated with ultrasonically welding the molybdenum-0.5% titanium alloy were more or less conclusively shown to be associated with material contamination. [Cracking [illegible] in D-31 can be [illegible] with the [illegible] power force programming!]

3. Based on sparse data ~~from scouting investigations~~, ultrasonic welds in these materials do not exhibit appreciably more strength decay at 2000°F than does the parent sheet material.

4. It appears that programming of the ultrasonic power and the associated static clamping force delivered by the ultrasonic welder will result in improved ultrasonic welds.

end
[illegible]
11-27-63

APPENDIX A

HIGH-TEMPERATURE WELD STRENGTH STUDIES

APPENDIX A

HIGH-TEMPERATURE WELD STRENGTH STUDIES

1. INTRODUCTION

After completion of the experimentation described in the main body of this report, supplementary studies were undertaken to determine the strength of ultrasonic welds in the three selected materials when exposed to elevated temperatures.

Specimens of each material were carefully prepared, welding threshold curves were established, and weldments were made at suitable machine settings. Some of these were tested in tensile-shear at room temperature and at one elevated temperature (2000°F), and others were sectioned and examined metallographically.

2. MATERIALS AND PREPARATION

a. Molybdenum-0.5% Titanium

Specimens of molybdenum-0.5% titanium alloy were prepared from 0.015-inch sheet which was residual from the primary program (Lot 2) and consisted of small pieces approximately 2 inches by 6 inches in size. Sufficient material was available to cut 63 coupons to the size 2 inches by 3/4 inch.

Based on work conducted under another program (11), it was found that removal of surface film improves material ductility. Therefore, prior to welding, the coupons were chemically etched in a solution of sulfuric acid (95% by weight), nitric acid (4.5%), hydrofluoric acid (0.5%), and chromic anhydride (18.8 grams per liter) for approximately 4 minutes. The coupon thickness after etching was approximately 0.013 inch.

b. Niobium-10% Titanium-10% Molybdenum Alloy

Additional D-31 alloy, 0.0175 inch thick, was obtained from DuPont for this supplementary work. Analysis revealed the oxygen content to be about 3000 ppm, which is about three times the normal tolerance. Higher-quality materials could not be obtained in time for completing the work.

This sheet material was sheared into coupons 3/4 inch wide by 2 inches long. For the same reason as noted above, these were etched in an aqueous solution containing 22% hydrofluoric acid, 8% nitric acid, and 15% sulfuric acid. The thickness after etching was 0.015 inch.

c. Tungsten

Pre-cut specimens of 0.010-inch tungsten were obtained from Fansteel Metallurgical Corporation. Two surface preparation methods were used. Some coupons were electropolished to 0.007 inch in an aqueous solution of sodium hydroxide and sodium nitrite. Others were etched in an aqueous solution of sodium hydroxide and potassium ferricyanide. The etching treatment did not measurably reduce the sheet thickness.

3. TEST PROCEDURES

Initial welding of each of the materials was carried out at varied power and clamping force levels and using Udimet-700 tips of 3/4 inch and 3 inch radius, in order to establish satisfactory conditions for welding. Threshold curves of strength vs. clamping force were constructed from data obtained in tensile-shear tests at room temperature.

Weldments produced at the selected settings were tested in tensile-shear in the Instron testing machine at a crosshead speed of 0.05 inch per minute. Some of the tests were conducted at room temperature and others were conducted at 2000°F in a vacuum furnace installed on the testing machine.

Bond quality was determined by visual examination of the external weld spot, observation of the mode of failure during testing, examination of the fracture surfaces, and metallographic examination of sectioned specimens.

4. TEST RESULTS AND DISCUSSION

a. Molybdenum-0.5% Titanium

The threshold curve for the molybdenum-0.5% titanium alloy was established by tensile-shear tests of welds made at 0.5 seconds. The curves derived from these data are shown in Figure 31, wherein each data point represents the average of three values.

Welding conditions of 3300 watts, 750 pounds, and 0.5 second with a 3/4-inch tip were chosen for additional welding tests to establish average room-temperature strength properties. The average of ten values yielded a room-temperature tensile-shear strength of 180 pounds.

Three specimens tested at 2000°F yielded values of 36, 91, and 204 pounds. The first specimen was a defective weld; examination of the fracture surfaces revealed that only a small portion of the contact area was bonded. The remaining two specimens displayed more uniform bonding over the entire contact surface. The average of the latter two values is 147 pounds.

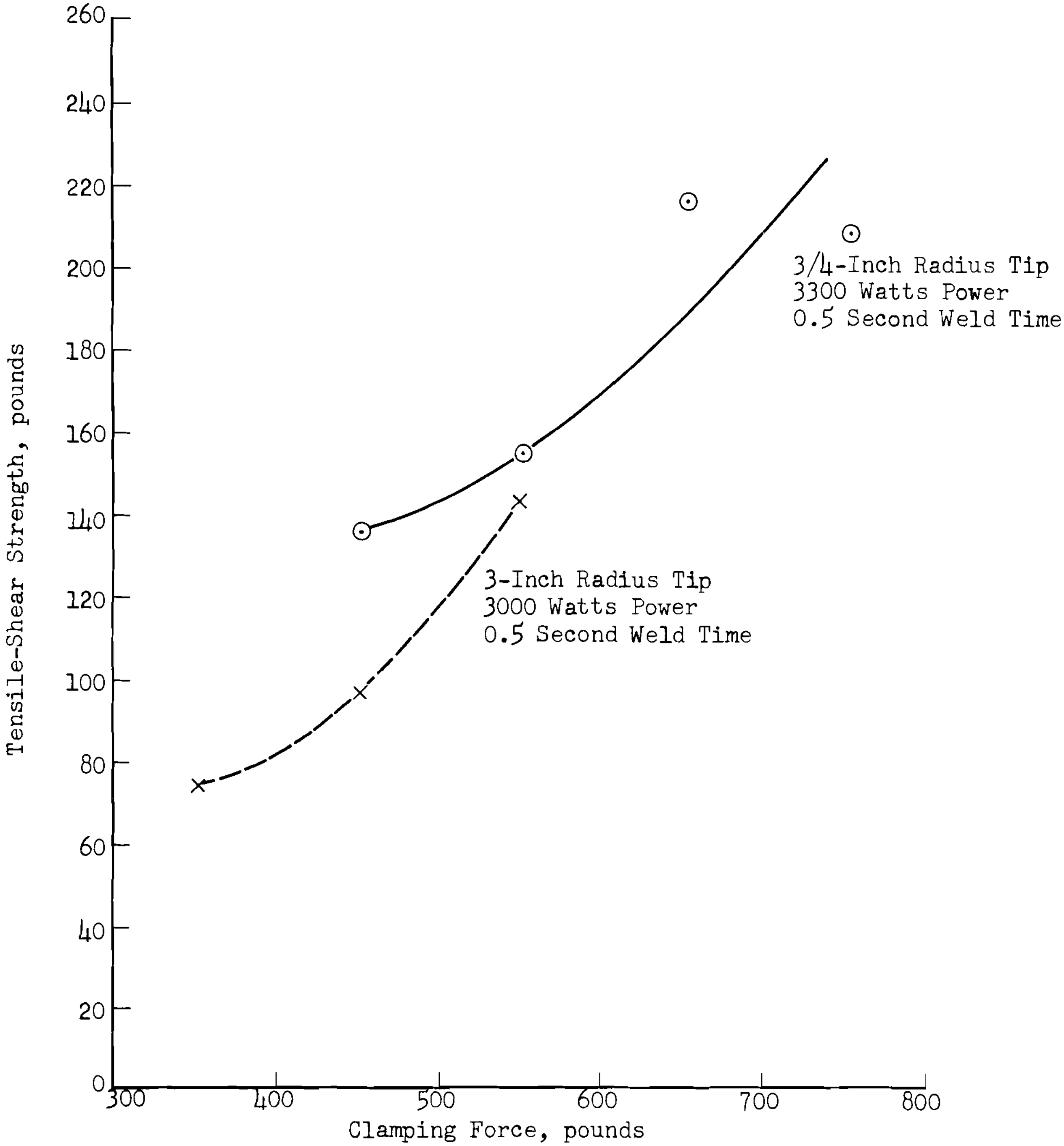


Figure 31

THRESHOLD CURVES
FOR 0.013-INCH MOLYBDENUM-0.5% TITANIUM ALLOY

On the basis of these values, weld-strength degradation at 2000°F is approximately 18 percent of the room-temperature weld strength. The decrease in ultimate tensile strength of commercial quality molybdenum-0.5% titanium alloy sheet at 2000°F has been reported to be approximately 50 per cent (32). The discrepancy may result from cracks in the weld zone. Metallographic examination of three specimens welded at the same machine settings revealed edge cracks in two of the three samples. Such cracks undoubtedly produce premature failure of the joint, and their effect may be less significant at the high testing temperatures. A photomicrograph of the weld structure in a sound joint is shown in Figure 32.

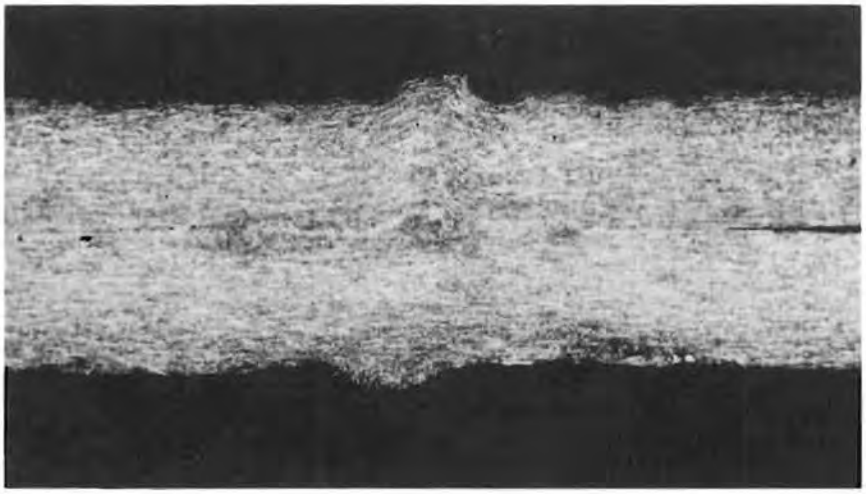
b. Niobium-10% Titanium-10% Molybdenum Alloy (D-31)

Threshold curves for the D-31 alloy welds are presented in Figure 33. When a 3-inch-radius tip was used, only a narrow range of clamping forces produced welds, and the higher clamping forces resulted in peripheral cracking. The 3/4-inch tip produced crack-free joints at the higher clamping forces. Microsections of welds made at 3300 watts, 650 pounds, and 0.5 second revealed no cracks; however, some voids and non-bonded areas were observed and the weld quality was unsatisfactory (Figure 34). Higher powers will be required to effectively join the 0.015-inch material.

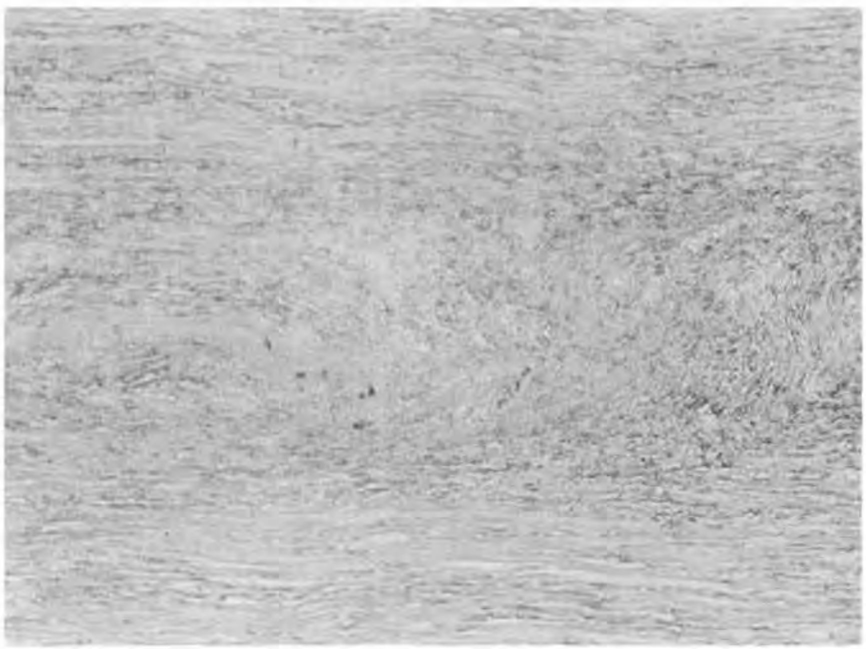
The average room-temperature strength of ten welds made at the above machine settings was 311 pounds. Of the three specimens tested at 2000°F, only a single value of 155 pounds was obtained; the remaining two specimens failed during the heating cycle. On the basis of this single strength value, the strength degradation was calculated as approximately 50 percent. The equivalent loss in strength of wrought stress-relieved sheet at elevated temperature is approximately 70 percent(7), which is in fair agreement with the weld strength degradation.

c. Tungsten

Welding machine settings for tungsten were difficult to establish. Specimens failed by brittle fracture of the sheet adjacent to the weld spot. Only the 3/4-inch-radius tip produced welds of sufficient strength consistency to plot the data, as shown in Figure 35. The chemically cleaned material was used to establish the threshold curves. Examination of welds made at 3300 watts, 550 pounds, and 0.5 second revealed cracks. Higher clamping forces also resulted in weld cracking and tip sticking. The average strength of ten specimens welded at the above conditions was 65 pounds. Two of the specimens failed by fracture of the sheet at the edge of the weld; the remaining samples failed by weld shear. A photomicrograph of a representative weld and the delamination-type cracking failure is shown in Figure 36.



Magnification: 40X



Magnification: 400X

Figure 32

PHOTOMICROGRAPHS OF ULTRASONIC WELD
IN 0.013-INCH MOLYBDENUM-0.5% TITANIUM ALLOY SHEET

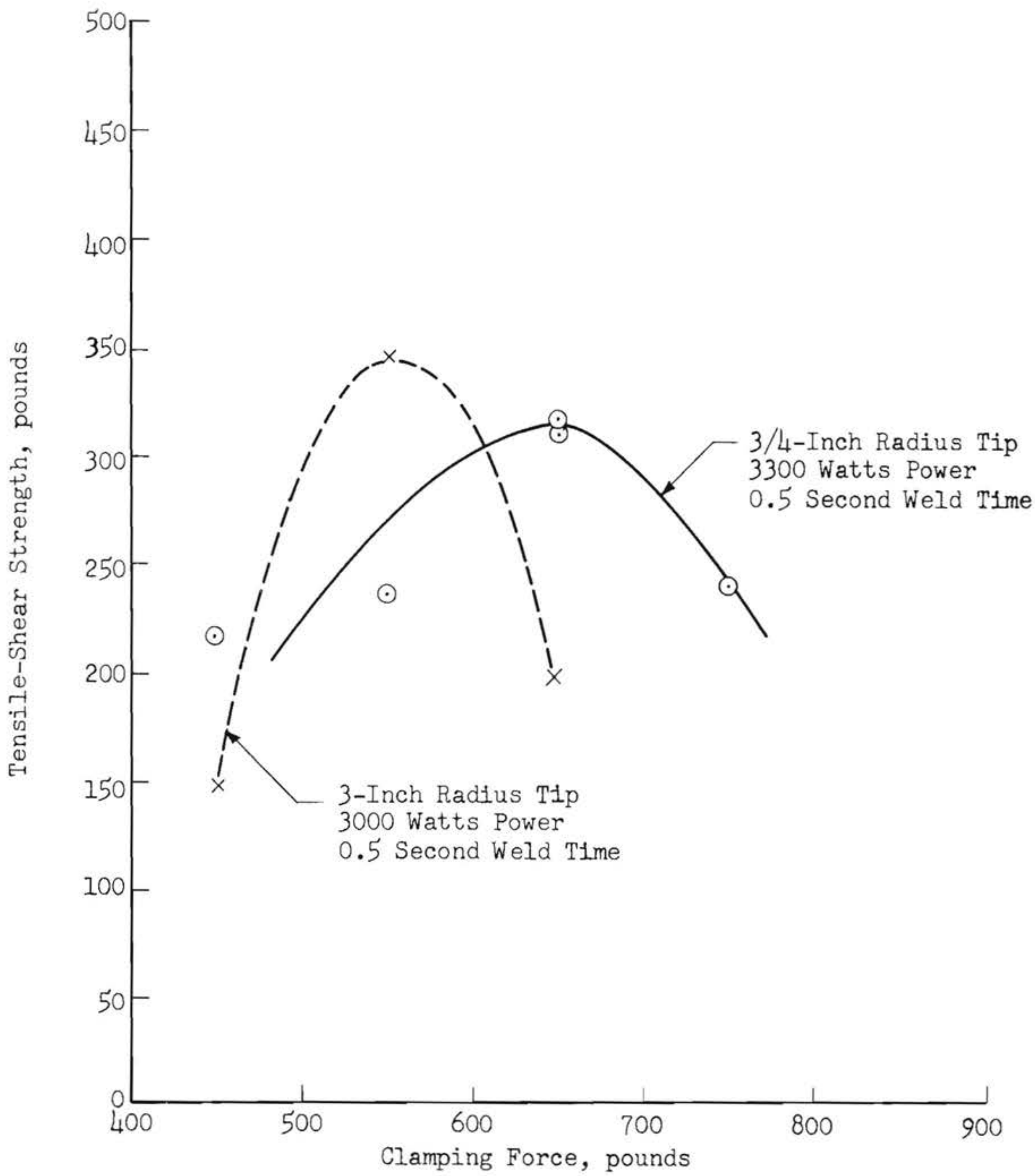
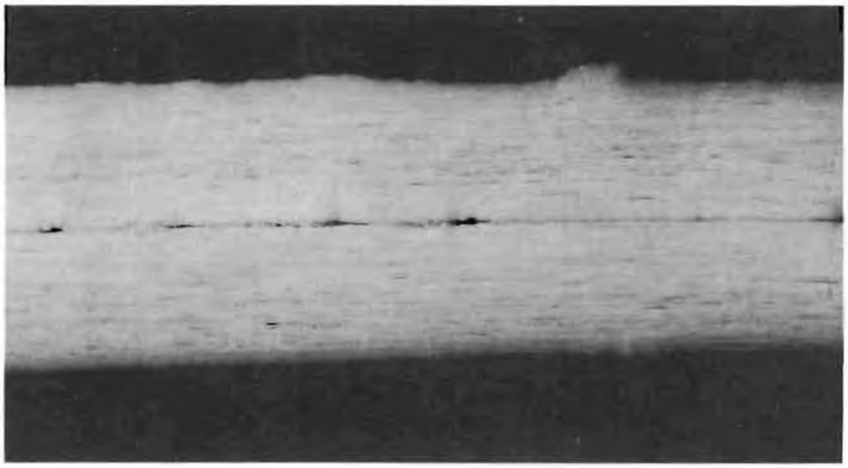
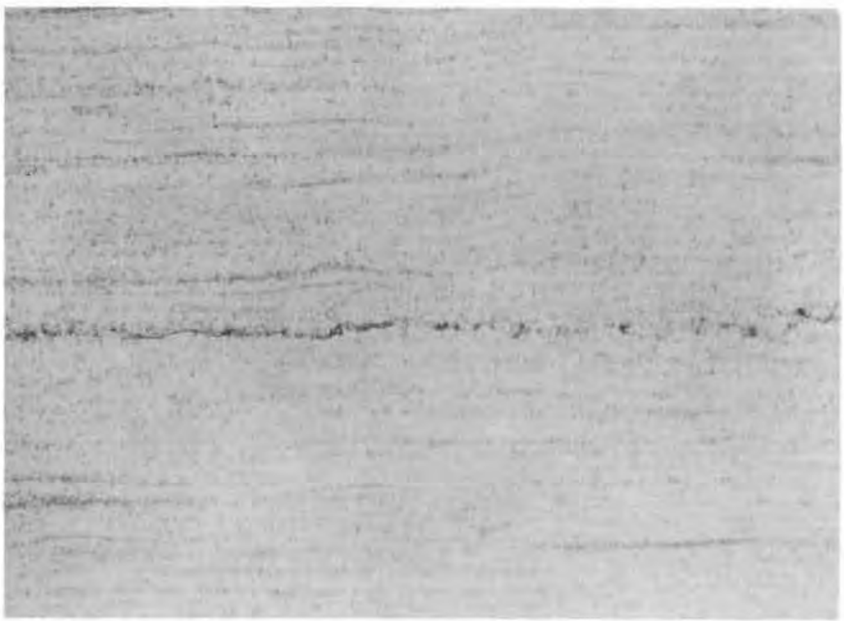


Figure 33

THRESHOLD CURVES
FOR 0.015-INCH NIOBIUM D-31 ALLOY



Magnification: 40X



Magnification: 400X

Figure 34

PHOTOMICROGRAPHS OF ULTRASONIC WELD
IN 0.015-INCH D-31 ALLOY SHEET

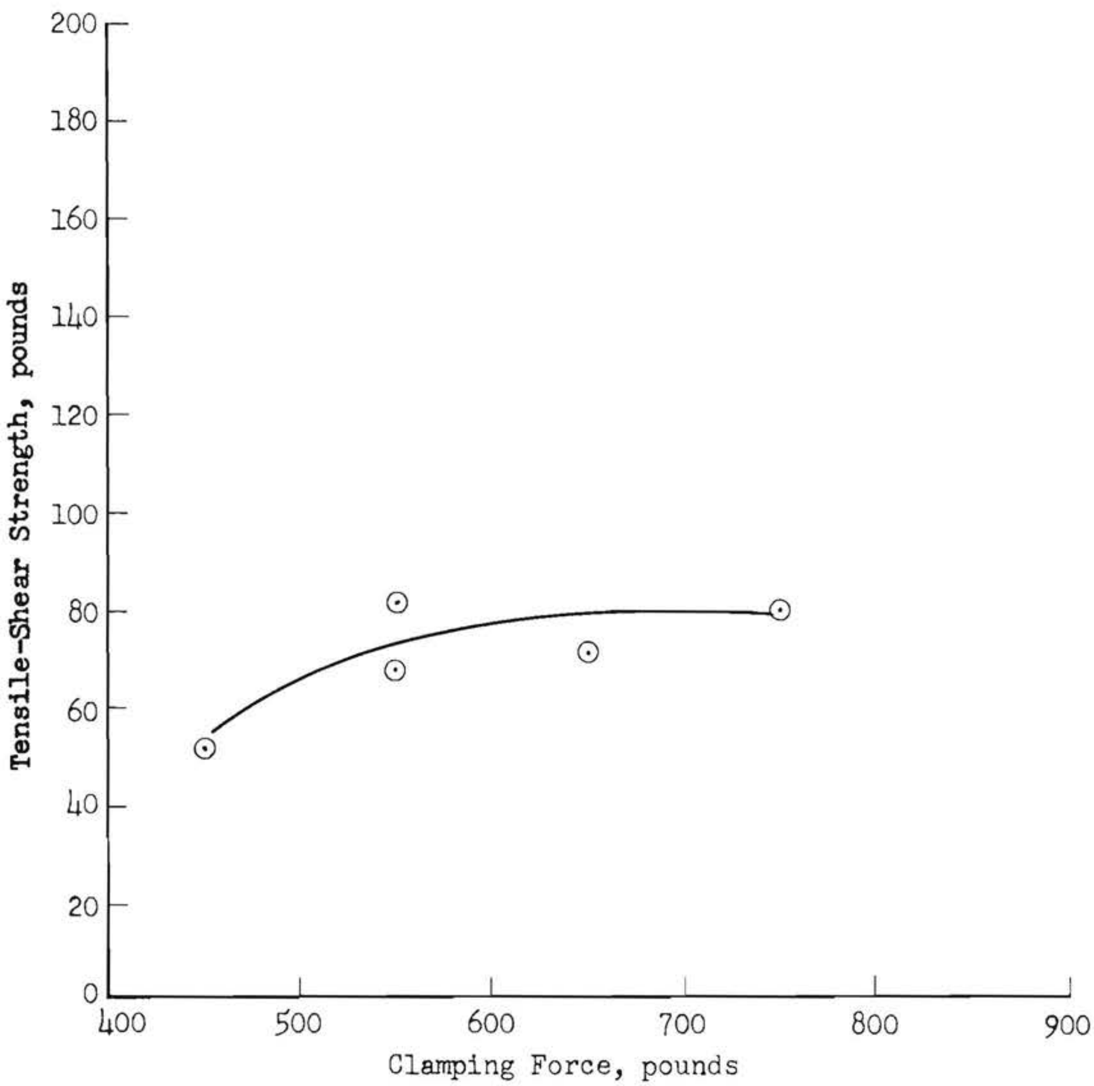
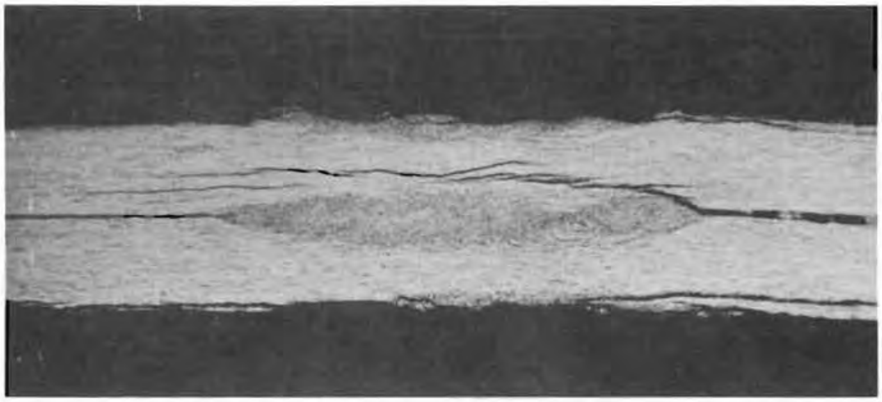


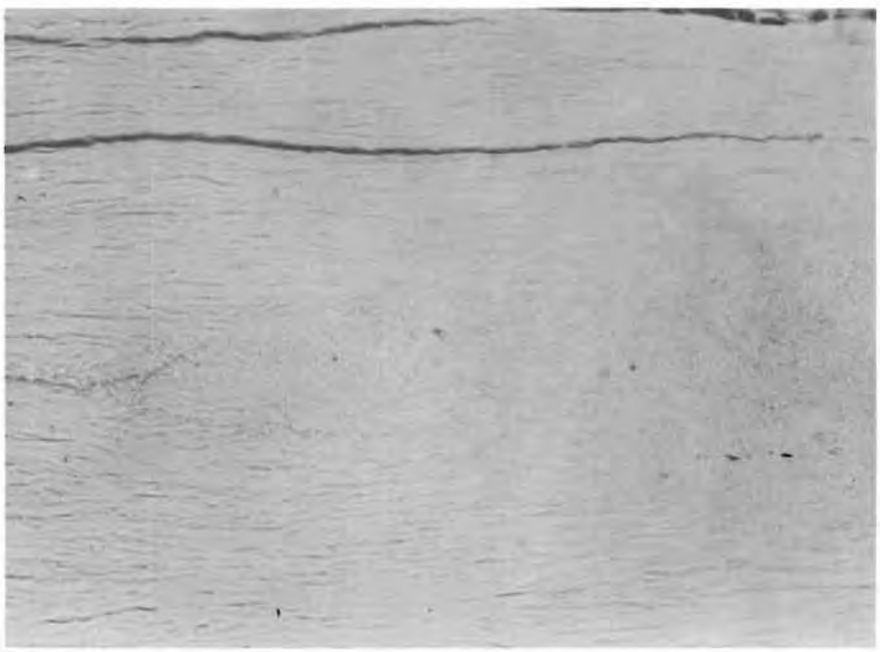
Figure 35

THRESHOLD CURVES
FOR 0.010-INCH TUNGSTEN

3/4-Inch Radius Tip
3300 Watts Power
0.5 Second Weld Time



Magnification: 40X



Magnification: 400X

Figure 36

PHOTOMICROGRAPHS OF ULTRASONIC WELD
IN 0.010-INCH TUNGSTEN SHEET

The unnotched tensile transition temperature for stress relieved tungsten sheet is reported as 150°C (33). The cracks which led to early failure at room temperature were apparently less significant in tests conducted at 2000°F. Values of 108, 24, and 120 pounds were obtained for an average of 84 pounds. Failure occurred by nugget pull-out (24 pounds) and by weld shear (108 and 120 pounds). No sheet fracture was obtained at the higher testing temperature.

5. CONCLUSIONS

As noted in the earlier studies, weld cracking proved to be a problem with the molybdenum-0.5% titanium alloy and with the tungsten. This can be alleviated with the use of power-force programming as discussed in Section VIII. These welding studies with the D-31 alloy have indicated that crack-free bonds can be obtained, but that power requirements are high.

On the basis of the limited data obtained in the high-temperature testing, it appears that ultrasonic weld strengths in these materials are degraded at 2000°F to no greater extent than the base materials themselves.

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